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Beyond the Energy Vector: Siting Green Methanol and Ammonia Through Social Multi-Criteria Evaluation—The Spanish Case

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Abstract

Renewable hydrogen derivatives—green methanol and green ammonia—are central to European industrial decarbonization, energy sovereignty and low-carbon transport, shipping in particular, yet decisions on where to site their production are driven by techno-economic criteria alone, sidelining social and territorial impacts. We ask where in Spain these derivatives should be produced when social need is placed at the centre of the decision. Using Social Multi-Criteria Evaluation, operationalized through the European Commission's SOCRATES tool, we rank the 50 Spanish provinces across four dimensions—technical, economic, social and human capital—from 17–19 public criteria aggregated with a non-compensatory Kemeny rule, and compare two scenarios (methanol and ammonia) tested by local and global weight-sensitivity analyses. Giving the social dimension an explicit, high weight shifts the geography obtained under the adopted weighting toward the south and interior. A weight-robust core—Murcia, Zaragoza, Asturias and an Andalusian arc—ranks highly for both derivatives, whereas the scenario leaders (Huelva for methanol, Sevilla for ammonia) are weight-dependent; within the present analytical framework, capturable CO_2 is the factor that differentiates the two geographies. The ranking should be read as just-transition *priority* under the adopted weighting—distinct from engineering feasibility and from realized welfare—rather than as an objectively optimal siting. Embedding social need as an explicit, quantified criterion yields a substantially different industrial geography, one more explicitly aligned with the distributive objectives of a just transition, and provides a transparent, replicable tool for transition planning.

Keywords: renewable hydrogen; green methanol; green ammonia; social multi-criteria evaluation; SOCRATES; just transition; industrial siting; territorial cohesion; Spain

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1. Introduction

Europe's energy system is at an inflection point. Decades of industrial prosperity built on imported fossil fuels left the continent dependent on external supply for a large share of its primary energy, a fragility laid bare by the 2022 gas-supply crisis. The response couples three goals that were once pursued separately—energy sovereignty, industrial competitiveness and deep decarbonization—and increasingly converges on a single idea: that the molecules which fossil fuels once provided must be replaced by "green" ones. Renewable hydrogen and its derivatives are the leading candidates to carry energy and feedstock into the parts of the economy that electricity cannot easily reach [1,2].

Among those derivatives, green methanol and green ammonia stand out. Both are established industrial commodities with mature synthesis routes and consolidated global

markets. Both are liquids, or easily liquefiable, so they fit existing storage and transport infrastructure. And both are front-runners as zero-carbon fuels for shipping, one of the hardest sectors to electrify [3]. Yet they differ in one decisive respect. Both start from the same primary input, renewable electricity and water, but methanol synthesis also needs a source of carbon, captured from biogenic or industrial CO_2, whereas ammonia fixes nitrogen from the air and needs no carbon at all [4–6]. That single difference, as this paper shows, is enough to reshape the map of where each derivative should be produced.

The appeal of these two carriers over hydrogen itself is largely logistical. Gaseous hydrogen has a low volumetric energy density and demands cryogenic or high-pressure handling, whereas green methanol is liquid at ambient conditions, with a volumetric energy density of roughly 15–16 MJ/L [7], and ammonia liquefies under mild pressure and doubles as a carbon-free energy carrier [8]; both slot into infrastructure that already exists. Their markets are also moving. Methanol is the more mature marine option, with a fast-growing order book of methanol-capable vessels, while ammonia is advancing through engine testing and first pilots as a leading candidate for deep-sea shipping [3]. The question this paper addresses is therefore not whether these molecules will be produced—announced project pipelines already signal that they will—but where, and for which derivative, that production should be located.

This is not a question with a single, obvious answer. The considerations that bear on it—renewable resource, water, grid and port access and cost, but also the social and territorial consequences of siting—are measured in different units and answer to different values. Answering it well therefore means weighing several incommensurable considerations at once.

Conventional siting studies weigh only two of them. Feasibility analyses of renewable hydrogen and its derivatives are built almost entirely on technical criteria—resource, grid, water, port access—and economic ones—levelized cost, capital, product price. These are necessary but not sufficient for a genuinely integral planning of the transition. A growing body of work on energy justice and just transitions argues that decarbonization has distributional and spatial consequences that must be part of the decision [9,10]. The principle of a *just transition*, enshrined in the European Green Deal and the Just Transition Fund, holds that the transformation of the energy system should actively contribute to territorial and social cohesion, rather than concentrating the benefits of decarbonization where prosperity already sits [11,12]. This study takes that principle as an operational premise. It starts from the hypothesis that the territories of greatest social need are not necessarily the worst candidates to host this new industry—and that, where technical and economic conditions are also reasonable, siting production there could help turn deployment into a catalyst for regional development—potentially creating skilled employment, helping anchor population and supporting local economies. These are policy mechanisms the study motivates but does not itself quantify.

The siting literature, however, rarely takes that view. Multi-criteria decision analysis (MCDA) is the standard tool for locating renewable-energy and power-to-X facilities, usually coupled with geographic information systems [13–17]. For renewable hydrogen in particular, a recent systematic review finds a field dominated by the Analytic Hierarchy Process and by technical and economic criteria—resource, water, land, and proximity to demand and infrastructure—mapped onto a single production pathway [18,19]. Studies of individual derivatives follow the same template: green-hydrogen and green-ammonia analyses weight solar and wind resource, water and transport, while social factors enter, if at all, as land-use constraints or acceptance proxies rather than as an explicit objective [20–22]. Three gaps follow. First, the social dimension is seldom an explicit, weighted objective. Second, the prevailing weighted-sum and AHP aggregations are fully compensatory, so

a strong techno-economic score can mask a severe social deficit—exactly the outcome a just-transition lens seeks to avoid. Third, derivatives that share infrastructure but differ in feedstock are rarely compared within one framework.

A second body of work sits on the other side of the same divide. The just-transition literature shows that decarbonisation pathways fall unevenly across regions and calls for "spatially just" planning, yet it seldom connects to the operational tools that decide where new industry actually lands [23,24]. Social multi-criteria evaluation (SMCE) is well placed to bridge the two. Conceived for value-laden, incommensurable public decisions, it has already been applied to renewable-energy conflicts, including wind-farm and solar siting in Spain [25–28].

We put this approach to work on Spain, a particularly instructive case. Spain is repeatedly identified as one of Europe's most favourable places to make these molecules, and its national hydrogen roadmap sets an early, ambitious target for renewable-hydrogen deployment [29]. Its solar irradiation is among the highest in Western Europe, its wind resource is first-rate in the interior, Galicia and the Strait of Gibraltar, and it combines an industrial legacy in petrochemicals, steel and fertilizers with a consolidated network of Atlantic and Mediterranean ports. Crucially for our purposes, these endowments are unevenly distributed. The provinces with the greatest solar resource, in the south and the Canary Islands, are often those of highest social vulnerability; the provinces with the strongest industry and human capital—Madrid, Barcelona, the Basque Country—have comparatively modest renewable resource; and the Galician provinces, rich in wind and ports, face severe depopulation. This variable geometry makes Spain an ideal setting in which the tension between techno-economic and social criteria—the very tension our method is built to arbitrate—appears in sharp relief.

Against this background, we place the social need of the territory—its need for productive transformation—at the centre of the siting decision, as an explicit, quantified criterion, and we do so comparatively for two derivatives. We operationalize this through the SMCE framework and the European Commission Joint Research Centre (JRC) SOCRATES tool, ranking the 50 Spanish provinces across four dimensions—technical, economic, social and human capital—in two parallel scenarios, green methanol and green ammonia. The contribution is fourfold, and it is worth stating precisely what is and is not new. Assigning a high weight to the social dimension is not, in itself, a methodological novelty—it is a normative choice. What is novel is the *combination*. First, we make social need an explicit, weighted objective and aggregate it with the other dimensions through a *non-compensatory social-choice* rule (Kemeny), so that a strong techno-economic score cannot silently offset a severe social deficit—in contrast to the compensatory AHP and weighted-sum schemes that dominate siting studies. Second, we compare methanol and ammonia within an identical framework, isolating capturable CO_2 as the feedstock that differentiates them *within the model* and tracing its effect on the resulting geography. Third, we subject every ranking to local and global weight-sensitivity analyses that separate robust recommendations from weight-dependent ones. Fourth, we release the model and data as an open, executable re-implementation, which lets us audit not only where the ranking is robust but also where it is fragile—and, as it turned out, to identify and report a material sensitivity to how count-based criteria are scaled. The result is a replicable, auditable tool—built entirely on public data—for planning a just industrial transition, one clear about the parts of its output that should be trusted and the parts that remain provisional.

The remainder of the paper is organized as follows. Section 2 describes the SMCE/SOCRATES framework, the four dimensions and their criteria, the weighting scheme and the data sources. Section 3 presents the provincial rankings for each derivative, their dimensional structure and their robustness. Section 4 compares the two geographies, dis-

cusses the CO_2 effect and the policy implications for a just transition, and states the study's limitations. Section 5 concludes.

2. Materials and Methods

2.1. Social Multi-Criteria Evaluation and the SOCRATES Tool

We adopt Social Multi-Criteria Evaluation (SMCE), a framework developed for the appraisal of public policies in settings where technical, economic and social considerations coexist and are mutually incommensurable [25,30]. Its founding premise is that comparing options such as *where to site an industry* cannot be reduced to a single yardstick: the relevant dimensions are measured in different units and answer to different values, and collapsing them into one monetary or physical score discards precisely the information a just-transition decision needs. SMCE keeps each criterion in its own terms and makes the trade-offs between them explicit and auditable.

Multi-criteria decision-making offers several families of methods for this task: value-aggregation approaches such as the Analytic Hierarchy Process [31], outranking methods such as ELECTRE [32] and PROMETHEE [33], and distance-based methods such as TOPSIS [34]; comprehensive treatments and guidance on method choice are given elsewhere [35,36]. SMCE belongs to the social-choice branch of the outranking tradition. Its aggregation rests on the theory of collective choice—Condorcet's pairwise majority and Arrow's analysis of its limits [37]—and, in particular, on the Kemeny–Young median, the ranking that best reconciles the pairwise verdicts of the criteria [38,39]. We adopt it, rather than the other non-compensatory outranking methods, for two concrete reasons. First, it rests purely on pairwise majority (a Condorcet logic) and so requires no criterion-specific preference and indifference thresholds of the kind ELECTRE and PROMETHEE need—extra parameters that would be hard to justify for social criteria and would add their own subjectivity. Second, the Kemeny median returns a single, complete social-choice ranking with a clear axiomatic characterization [39], which is what a transparent, replicable siting recommendation calls for, and it is the rule implemented in SOCRATES. In short, that non-compensatory, social-choice logic is exactly what a just-transition siting problem requires.

We implement SMCE with SOCRATES (Social multi-CRiteria AssessmenT of European policieS), a tool developed by the Decision Analysis Laboratory of the JRC and used in European Commission impact assessments [40]. Choosing an established, publicly documented tool over a bespoke procedure is deliberate: the rankings it produces are reproducible, its assumptions are explicit, and its mathematical machinery has been independently described [25,41].

To keep the analysis independent of any single tool, we also re-implemented the SMCE procedure from scratch as an open Python 3.3.14 routine. It reads the same public impact matrix, builds the weighted non-compensatory outranking and solves the Kemeny median ordering (Appendix B). The open re-implementation reproduces the SOCRATES rankings closely: the two orderings share the same methanol leader and the same robust core, with a Spearman rank correlation of $\rho = 0.91$ for methanol and $\rho = 0.84$ for ammonia (Table A6). The residual differences trace to SOCRATES's internal preference thresholds, which our routine does not replicate; for ammonia they concentrate on the very leader that the sensitivity analysis independently flags as weight-dependent. Unless noted, the rankings below are the SOCRATES output; the dimension and sensitivity analyses (Sections 3.1 and 3.4) are produced with the open implementation, whose code and data we release for scrutiny.

2.2. Model Components

SOCRATES applies three interrelated components. The *multi-criteria* component organizes the input into an impact matrix—one row per province, one column per criterion—and produces a ranking through the non-compensatory Kemeny median rule [38,39], solved with the Azzini–Munda algorithm [41].

Formally, let A be the set of the 50 provinces (alternatives) and C the set of criteria, each with weight $w_c \geq 0$ and $\sum_{c \in C} w_c = 1$. For a pair of provinces $a, b \in A$ and a criterion c, a single-criterion preference index records the direction of the comparison,

$$P_c(a,b) = \begin{cases} 1, & a \succ_c b, \\ \frac{1}{2}, & a \sim_c b, \\ 0, & b \succ_c a, \end{cases} \tag{1}$$

where $\succ_c$ and $\sim_c$ denote strict preference and indifference on criterion c (with the optimization direction of Table 1). These are aggregated into a weighted outranking (concordance) matrix,

$$e(a,b) = \sum_{c \in C} w_c \, P_c(a,b), \tag{2}$$

which measures the weighted share of criteria for which a is at least as good as b. The Kemeny median ranking R^* is the linear order that best agrees with this pairwise evidence,

$$R^* = \arg\max_{R \in \Pi(A)} \sum_{\substack{(a,b) \in A \times A \\ a \succ_R b}} e(a,b), \tag{3}$$

where $\Pi(A)$ is the set of all rankings of A and $a \succ_R b$ means a precedes b in R. Equivalently, R^* minimizes the weighted number of pairwise inversions (the Kendall distance) with respect to the criteria.

Non-compensation is the property that matters most here, and it should be understood precisely. It means that the *magnitude* of an advantage on one criterion cannot mechanically offset a disadvantage on another: the Kemeny rule counts, for every pair of provinces, how many weighted criteria favour one over the other, not by how much, so a province cannot climb simply by being spectacular on a single dimension while collapsing elsewhere. It does *not*, however, impose a per-dimension veto. A province that performs well across several weighted criteria can still outrank one with a serious weakness in a single dimension—indeed our results show this, with Vizcaya ranking sixth for ammonia despite a low social-need score. Non-compensation therefore blocks the cardinal "buying back" of a deficit, not every trade-off. That is also what makes it legitimate to read the weights as coefficients of *importance* rather than as rates of substitution, which would not hold under a weighted sum [25,42].

The *equity* component, designed to integrate the qualitative appraisals of identifiable stakeholders, is not applied here: the alternatives are territories rather than policy options with distinct interest groups, so there is no equity matrix to build. This is a deliberate boundary of the study: because the equity component is not applied, the analysis captures the *distributive* and territorial component of a just transition, not procedural justice, recognition or participation, a distinction we return to in the interpretation. The *sensitivity* component tests how far the results depend on the analyst's choices. A local analysis varies one weight or criterion at a time; a global analysis explores the weight space by Monte-Carlo random sampling from the simplex [43,44], rejecting draws that exceed the per-dimension cap. Concretely, dimension-weight vectors $W = (W_{\text{tech}}, W_{\text{econ}}, W_{\text{soc}}, W_{\text{hum}})$ are drawn from the simplex subject to a cap $W_d \leq 0.5$ that keeps any single dimension from unilaterally determining the order (a "dictator" dimension) while still permitting strong emphasis on

any one of them; for each draw the ranking $R^*(W)$ is recomputed via Equations (3)–(5), and the empirical rank distribution of every province is accumulated,

$$f_a(r) = \frac{1}{M} \sum_{m=1}^{M} \mathbf{1}\left[\text{rank}_{R^*(W^{(m)})}(a) = r\right], \tag{4}$$

over M samples $W^{(1)}, \ldots, W^{(M)}$. We draw $M = 1500$ weight vectors per scenario; the median ranks are stable well below this size (Section 3.4), so the sample is comfortably in the converged regime. To probe the modelling choices further, we additionally (i) repeat the analysis under caps of 0.4, 0.6 and no cap, and (ii) extend the sampling so that the criterion weights *within* each dimension also vary (Monte-Carlo over the criterion simplex), not only the dimension weights. The output is therefore not a single ordering but a distribution of orderings, from which we read which positions are structural and which are artefacts of one particular weighting.

2.3. Alternatives, Dimensions and Criteria

The alternatives are the 50 Spanish provinces (NUTS3). Criteria are grouped into four dimensions—technical, economic, social and human capital—built entirely from public, contrastable sources covering 2023–2025. Two parallel scenarios share the same structure and most criteria but differ in the technical dimension: criteria C7 (capturable industrial CO_2) and C8 (capturable biogenic CO_2) apply only to the methanol scenario, since ammonia synthesis needs no carbon feedstock. Table 1 lists the full set of 17–19 criteria with their optimization direction, indicator, source and scenario; the paragraphs below give the rationale for each, dimension by dimension.

The choice of dimensions and criteria warrants explanation, as it conditions everything that follows. It followed an explicit, four-step protocol. First, we assembled a pool of candidate criteria from the literature: the technical and economic variables that dominate GIS–MCDA studies of renewable and hydrogen siting [16,18,20], together with the social and human-capital indicators used in just-transition and regional-development research [9,23]. Second, each candidate was screened against four rules: relevance to a siting decision, measurability from public provincial statistics, non-redundancy with criteria already retained, and salience for policy. Third, the survivors were organized into four dimensions—technical, economic, social and human capital—a decomposition consistent with the multi-capital framing of territorial assessment [36]. Fourth, the set was refined iteratively through informal discussions with colleagues working on hydrogen and on social-impact assessment at our institution (acknowledged below). Where a canonical indicator existed we preferred it: the social dimension, for instance, is anchored on the AROPE rate (C12), the European Union's official measure of poverty and exclusion, which keeps that dimension comparable and auditable. We make no claim that this is the only defensible set; it is a deliberate, explicit modelling choice, and Section 3.5 tests directly how far the results depend on it.

2.3.1. Technical Dimension

The technical dimension captures the physical viability of large-scale electrolysis and derivative synthesis. Solar and wind resource (C1, C2) are the primary energy inputs. C1 uses annual global horizontal irradiation, which is technology-neutral; C2 uses the mean wind speed at 100 m taken at each province's site of maximum wind resource rather than a provincial average or capital-based value, because turbines are sited where the resource is best and a representative or capital-based value would systematically understate the deployable potential of provinces with strong but geographically concentrated wind. Criteria C1 and C2 capture renewable-resource potential, not the firm, economically viable power

supply required for continuous electrolyser operation, which depends on generation mix, storage, curtailment and grid interaction and is a matter for site-level techno-economic assessment. Water availability (C3) enters with inverse direction through the Water Exploitation Index by hydrographic basin, because electrolysis consumes roughly nine litres of deionized water per kilogram of hydrogen and water stress is a real constraint in the southeast. Each province is assigned the WEI+ of the hydrographic basin covering most of its territory (the more water-stressed basin where a province spans basins of markedly different stress); this provincial assignment necessarily smooths within-province basin variation and is treated as a screening proxy. Three further criteria capture siting frictions: land free of Natura 2000 protection (C4)—the EU network of protected areas—proxies permitting feasibility, since projects inside these areas face longer and more uncertain assessment; it is a permitting proxy rather than a measure of physically available land, which also depends on zoning, ownership, slope and other constraints not captured here—for example, buffer distances from urban areas (typically 500–1000 m) and roads (200–300 m) for the renewable installations, and, for the hydrogen plant itself, the Seveso III Directive (2012/18/EU, transposed by Spanish Royal Decree 840/2015), which for hydrogen storage above 5 t requires site-specific safety distances set by risk assessment rather than fixed thresholds, and so cannot be resolved at this pre-feasibility, provincial scale. Grid access capacity (C5) reflects the connection headroom published by the system operator, where the grid serves to complement on-site renewable generation and power auxiliary loads rather than to receive injected electricity. C5 measures the headroom to connect new demand published by the system operator, apportioned from the autonomous-community level; it does not capture the adequacy of local renewable generation, transmission-network constraints or the cost of grid reinforcement, so it indicates connection opportunity rather than guaranteed, affordable supply. Port access (C6), with inverse direction, measures the road distance to the nearest port equipped for bulk liquids and chemicals, which is decisive both for export and for bunkering fuel to ships; distance captures logistical proximity only, not port capacity or the availability of methanol/ammonia handling infrastructure, which vary across ports. The last two criteria are specific to methanol. C7 quantifies capturable industrial CO_2 from registered facilities—used as a proxy for the presence and scale of nearby capturable point sources, not a claim that all registered emissions are technically or economically capturable and deliverable to a plant. The realistic capture rate depends on the capture configuration (post-, pre- or oxy-combustion), the technology and the flue-gas CO_2 concentration, which vary by facility and which we do not model; estimating them for every emitter is beyond a national-scale assessment. Because the criterion is normalized across provinces, this simplification has a limited effect provided capture rates are broadly similar, but provinces whose emissions come mainly from low-concentration sources may be somewhat overestimated. C8 is the cheaper, relatively pure biogenic CO_2 released when biogas is upgraded to biomethane, estimated from reported upgrading capacity (Sedigas) apportioned to provinces; a uniform capture rate (about 90%) is assumed and, because the criterion is normalized, that rate does not affect the ranking. Like C7, C8 indicates potential availability rather than contracted supply. Producing one tonne of green methanol requires about 1.37 tonnes of CO_2, so proximity to carbon sources becomes a genuine siting factor.

Table 1. Criteria of the SOCRATES model, by dimension. "Dir." gives the optimization direction (MAX: higher score is better; MIN: lower is better). Social criteria are directional so that greater territorial need scores higher. Scenario: both derivatives unless noted (C7–C8 apply to methanol only).

Code	Criterion	Indicator (Main Source)	Dir.	Scenario
Technical dimension (25%)				
C1	Solar resource	Annual mean GHI, kWh/m^2/yr (PVGIS 5.3, SARAH3)	MAX	Both
C2	Wind resource	Mean wind speed at 100 m, maximum-resource site (Global Wind Atlas 3.3; ERA5)	MAX	Both
C3	Water availability	Water Exploitation Index WEI+ by hydrographic basin (MITERD, 3rd cycle)	MIN	Both
C4	Land free of Natura 2000	% area outside Natura 2000 (SAC + SPA) (MITERD, 2024)	MAX	Both
C5	Grid access capacity	Available demand connection capacity (REE GRT, 2026)	MAX	Both
C6	Port access	Road distance to nearest bulk-liquids/chemicals port (Puertos del Estado)	MIN	Both
C7	Capturable industrial CO_2	Annual industrial CO_2, kt (EEA/PRTR IRD v13, 2022)	MAX	Methanol
C8	Capturable biogenic CO_2	Biogenic CO_2 from biomethane upgrading (Sedigas, 2023)	MAX	Methanol
Economic dimension (20%)				
C9	Industrial weight	Industrial GVA % of total (INE CRE, 2023)	MAX	Both
C10	Renewable H_2 projects	No. of projects at TRL ≥ 7 (IIT-ICAI H_2 Observatory, 2025; AeH2)	MAX	Both
C11	Industrial H_2 investment	Gross FDI flows in H_2-chain CNAE sectors (DataInvex, 2023)	MAX	Both
Social dimension (40%)				
C12	Social vulnerability	Adjusted AROPE rate (INE ECV, 2025; EAPN-ES)	MAX	Both
C13	Unemployment rate	Annual mean unemployment 2024 (INE EPA)	MAX	Both
C14	Depopulation index	% municipalities $<$ 12.5 inhab/km^2 + 2011–2024 change (MITERD; INE)	MAX	Both
C15	Renewables conflict	Composite conflict index: litigation, moratoria, opposition (CENDOJ; press)	MIN	Both
Human-capital dimension (15%)				
C16	Population 25–44	% of provincial population (INE Padrón, 2024)	MAX	Both
C17	Active STEM graduates	% active population with STEM degree (INE; Min. Univ.)	MAX	Both
C18	Industrial VET supply	No. of centres in 4 industrial VET families (TODOFP, 2022–23)	MAX	Both
C19	Engineering degrees	No. of active engineering Bachelor programmes (RUCT, 2024)	MAX	Both

2.3.2. Economic Dimension

The economic dimension gauges the strength of the industrial fabric and the momentum of the emerging hydrogen sector. Industrial weight (C9) is the share of industrial gross value added in provincial output, a proxy for latent hydrogen demand and for compatible infrastructure and know-how. The count of renewable hydrogen projects at TRL 7 or above (C10) captures deployment momentum; using the number of mature projects rather than announced gigawatts guards against large-scale announcements that never clear financing and permitting, at the cost of not reflecting project scale or capacity. Industrial hydrogen investment (C11) uses gross foreign direct investment flows into the CNAE sectors along the hydrogen value chain, a single-year flow that is volatile and an imperfect proxy for durable industrial capacity. Both are absolute measures, chosen to capture the *absolute* capacity a province offers rather than its capacity per head, which is the quantity relevant to siting; they consequently favour larger provinces. In Section 3.5 we report a per-capita re-specification of these criteria, which—measuring a different quantity—reorders the provinces appreciably; we present both encodings and adopt the absolute one as the measure appropriate to a capacity criterion.

2.3.3. Social Dimension

The social dimension—the heaviest in the model—measures the territory's need for productive transformation. Its criteria are directional, so that greater need scores higher. Social vulnerability (C12) uses the AROPE rate, the EU's standard synthetic measure of the population at risk of poverty or exclusion. Unemployment (C13) uses the 2024 annual mean, whose interprovincial range is very wide. The depopulation index (C14) combines the share of sparsely populated municipalities with recent population change, prioritizing the structural over the dynamic component. Renewables conflict (C15) enters with inverse direction and is built as a composite of three ordinally coded components over 2022–2024: administrative litigation against renewable projects (from the CENDOJ and vLex case-law databases), the presence of a regional moratorium or specific tax, and organized local opposition reported in the specialized press [45]. Each component is coded on a common ordinal scale, normalized, and averaged into a single index; provinces with no recorded events take the minimum. We deliberately relabel this criterion "conflict" rather than "acceptance": it records *observed contestation*, and the absence of recorded conflict need not indicate acceptance—it may instead reflect fewer projects, weaker mobilization capacity or unequal access to legal remedies—a limitation we make explicit in Section 4.7. Higher conflict therefore lowers a province's suitability, without being read as a direct measure of social acceptance. The four social indicators enter with equal within-dimension weight and capture complementary facets of the need for productive transformation—material vulnerability (C12), labour-market slack (C13), demographic thinning (C14) and social acceptance (C15)—rather than one construct measured four times; their low mutual correlation (Section 3.5) confirms that they are largely non-redundant, so the dimension is not dominated by any single facet.

2.3.4. Human-Capital Dimension

The human-capital dimension evaluates the availability of technical talent to staff a new industry. It combines the share of the population aged 25–44 (C16), the group with the greatest capacity to adapt to new industrial activity; the share of the active population holding a STEM degree (C17); the supply of industrial vocational training, measured as the number of centres authorized in four hydrogen-relevant VET families (C18); and the number of active engineering Bachelor programmes in the province (C19).

2.4. Weighting Scheme

Weights are assigned at the dimension level and distributed evenly among the criteria within each dimension, so that a dimension's importance is independent of how many criteria it contains [41]. Writing $d(c)$ for the dimension of criterion c, W_d for the weight of dimension d and n_d for the number of its active criteria, the criterion weights are

$$w_c = \frac{W_{d(c)}}{n_{d(c)}}, \qquad \sum_d W_d = 1, \qquad (W_{\text{tech}}, W_{\text{econ}}, W_{\text{soc}}, W_{\text{hum}}) = (0.25, 0.20, 0.40, 0.15). \tag{5}$$

Because the technical dimension has eight criteria for methanol but six for ammonia (C7–C8 excluded), its 25% is redistributed evenly over the criteria active in each scenario (3.125% each for methanol; 4.17% for ammonia), keeping the dimension's relative importance constant across scenarios.

The weighting is a deliberate normative choice, not the output of a statistical procedure. Giving the social dimension the largest single weight is the analytical expression of the paper's premise: to direct deployment toward the territories with the greatest need for transformation. We do not present this weighting as objectively correct; we present it as an explicit, defensible value judgement, and we test its influence throughout via the

global sensitivity analysis of Section 2.2, reporting which results survive re-weighting and which do not. This 25/20/40/15 allocation is a deliberate policy choice rather than an empirical finding: the social dimension leads because prioritizing territorial need is the paper's premise, and the global sensitivity analysis (Section 3.4) deliberately varies the weights so that no result rests on this specific split.

2.5. Data and the Difference Between Scenarios

All criteria derive from public sources spanning 2023–2025, detailed in Appendix A. Where an indicator was available only at the level of the autonomous community—as with grid access capacity—its provincial value was estimated by apportioning the regional figure, a simplification that may attenuate real differences between provinces of the same community. A small number of criteria rest on proxy variables, most notably renewables conflict (C15) approximated from litigation, moratoria and press records—a measure of observed contestation, not of acceptance; these choices, and their implications, are revisited in Section 4.7.

The two scenarios are identical except for criteria C7–C8. Any difference between the methanol and ammonia rankings can therefore be traced to a single factor—the methanol pathway's dependence on capturable CO_2—which is what lets us read the comparison of Section 4 as a controlled contrast rather than a coincidence of two separate models.

3. Results

Throughout, SOCRATES returns an ordinal ranking of the 50 provinces—the Kemeny median order—rather than a cardinal score. Positions are therefore read relative to one another, and always alongside the sensitivity analysis of Section 3.4, which tells us how much of each ordering is structural. We present the methanol scenario first, then the ammonia scenario, and reserve the head-to-head comparison for the Discussion.

3.1. Green Methanol: The General Ranking

Huelva (H) heads the methanol ranking (Figure 1; province codes are those used throughout the maps, with the full key in Table 2). Its lead comes not from dominance in any single dimension but from a balanced profile across all four: a high technical position driven by port access and the capturable industrial CO_2 of the Huelva chemical hub, a relevant industrial base, and the significant social need characteristic of the Spanish south. That combination—resource, infrastructure, capturable carbon and need—is precisely what the model rewards for methanol. Murcia (MU) and Zaragoza (Z) complete the podium by opposite routes. Murcia rests on a strong economic dimension and notable human capital, reinforced by high social need and CO_2 availability. Zaragoza is strong on the technical and economic dimensions, yet its comparatively low social profile keeps it from first place under the 40% social weight. That is already a telling sign of how decisively the social priority reorders a purely techno-economic map.

Ciudad Real (CR) illustrates the same mechanism from the other side. With only a modest technical dimension, it climbs to fourth on the strength of high social need and a hydrogen project pipeline anchored in the Puertollano hub—an ascent that a resource-and-cost screen would never produce. The upper tier is completed by an Andalusian and Asturian-industrial arc—Asturias (O), Sevilla (SE), Vizcaya (BI), Cádiz (CA), Almería (AL) and Córdoba (CO)—where strong industrial fabric and marked social need coexist. At the other extreme, Madrid (M) falls to 45th. It leads human capital and ranks well economically, but it comes last in the technical dimension—no available land, water or accessible CO_2 in a densely urban setting—and its social need is low. Baleares (IB), Lugo (LU), Cantabria (S),

Álava (VI) and Soria (SO) close the table, held back by technical or logistical constraints or by low social need.

Table 2. Full provincial suitability rankings for green methanol and green ammonia (SOCRATES Kemeny median order). Positions 1–25 (left) and 26–50 (right). The two-letter tag before each province is its standard Spanish province code (as used on the maps); this table doubles as the code-to-name key for the figures.

#	Methanol	Ammonia	#	Methanol	Ammonia
1	**H** Huelva	**SE** Sevilla	26	**CU** Cuenca	**A** Alicante
2	**MU** Murcia	**MU** Murcia	27	**GC** Las Palmas	**TO** Toledo
3	**Z** Zaragoza	**Z** Zaragoza	28	**PO** Pontevedra	**GC** Las Palmas
4	**CR** Ciudad Real	**CR** Ciudad Real	29	**OR** Ourense	**AB** Albacete
5	**O** Asturias	**O** Asturias	30	**SA** Salamanca	**LE** León
6	**SE** Sevilla	**BI** Vizcaya	31	**AB** Albacete	**TF** S.C. Tenerife
7	**BI** Vizcaya	**CA** Cádiz	32	**ZA** Zamora	**OR** Ourense
8	**CA** Cádiz	**AL** Almería	33	**AV** Ávila	**ZA** Zamora
9	**AL** Almería	**MA** Málaga	34	**B** Barcelona	**SA** Salamanca
10	**CO** Córdoba	**CO** Córdoba	35	**HU** Huesca	**AV** Ávila
11	**BU** Burgos	**GR** Granada	36	**L** Lérida	**B** Barcelona
12	**GR** Granada	**J** Jaén	37	**P** Palencia	**GI** Gerona
13	**CC** Cáceres	**CU** Cuenca	38	**NA** Navarra	**L** Lérida
14	**J** Jaén	**H** Huelva	39	**LO** La Rioja	**HU** Huesca
15	**BA** Badajoz	**BU** Burgos	40	**C** La Coruña	**TE** Teruel
16	**V** Valencia	**CC** Cáceres	41	**TF** S.C. Tenerife	**P** Palencia
17	**A** Alicante	**BA** Badajoz	42	**TE** Teruel	**SG** Segovia
18	**MA** Málaga	**V** Valencia	43	**SG** Segovia	**M** Madrid
19	**CS** Castellón	**CS** Castellón	44	**GI** Gerona	**SO** Soria
20	**GU** Guadalajara	**GU** Guadalajara	45	**M** Madrid	**VI** Álava
21	**SS** Guipúzcoa	**T** Tarragona	46	**SO** Soria	**LO** La Rioja
22	**T** Tarragona	**PO** Pontevedra	47	**VI** Álava	**LU** Lugo
23	**VA** Valladolid	**VA** Valladolid	48	**S** Cantabria	**NA** Navarra
24	**LE** León	**C** La Coruña	49	**LU** Lugo	**S** Cantabria
25	**TO** Toledo	**SS** Guipúzcoa	50	**IB** Baleares	**IB** Baleares

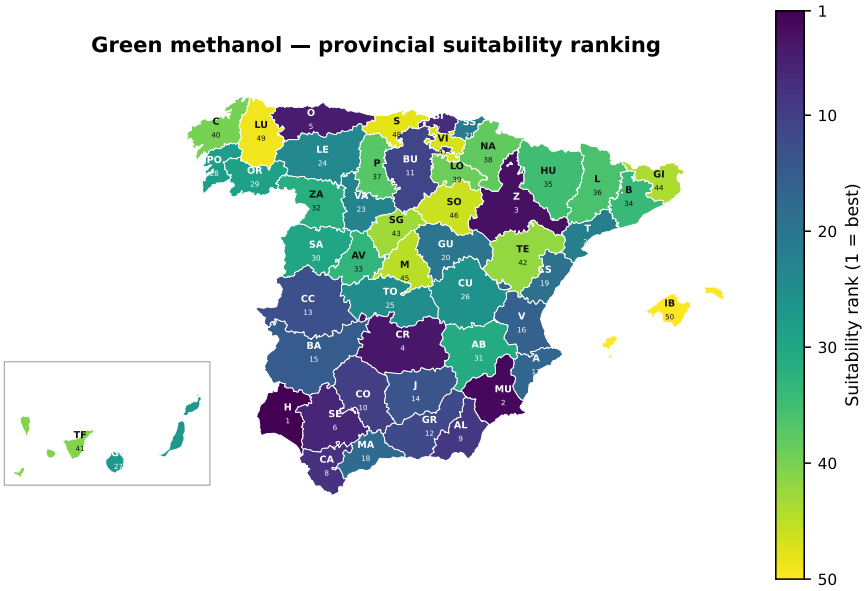


Figure 1. Green-methanol suitability ranking of the 50 Spanish provinces (Kemeny median order; 1 = most suitable). Each province is labelled with its standard Spanish province code and, below it, its rank; Table 2 is the code-to-name key. Canary provinces shown in the inset box. Rankings from the SOCRATES model.

Dimension by Dimension

Reading the four dimensions separately shows where each province's overall position comes from. The *technical* dimension is led by the wind-rich northwest and the Castilian–Leonese plateau—A Coruña (C), León (LE), Burgos (BU), Palencia (P), Salamanca (SA) and Zamora (ZA)—which combine abundant renewable resource, available land and grid headroom. The methanol-specific carbon criteria then apply a correction that a pure resource map would miss, lifting industrial, port-connected provinces such as Sevilla, Tarragona (T) and Huelva into the upper range. The *economic* dimension is headed by Asturias, on the strength of its industrial weight, followed by Guipúzcoa (SS), Murcia, Álava and Zaragoza. Badajoz (BA) and Cáceres (CC) are the surprise here: modest in traditional industry, they climb on the size of their hydrogen project pipelines, which shows how the project criterion rebalances the strictly industrial picture. The *social* dimension, the model's heaviest, reproduces the Spanish territorial divide with unusual clarity: Jaén (J), Córdoba, Granada (GR), Almería, Cádiz, Ciudad Real and Toledo (TO) lead—the interior and south of greatest need. The *human-capital* dimension is led by Madrid and the large urban provinces, whose concentration of young, qualified population and engineering capacity is the mirror image of the social map. Figure 2 maps the four dimension sub-rankings, making the contrast visible: the technical optimum in the Ebro valley and the northwest, the economic strength of the industrial north, the social need of the south and interior, and the human capital of the metropolitan cores.

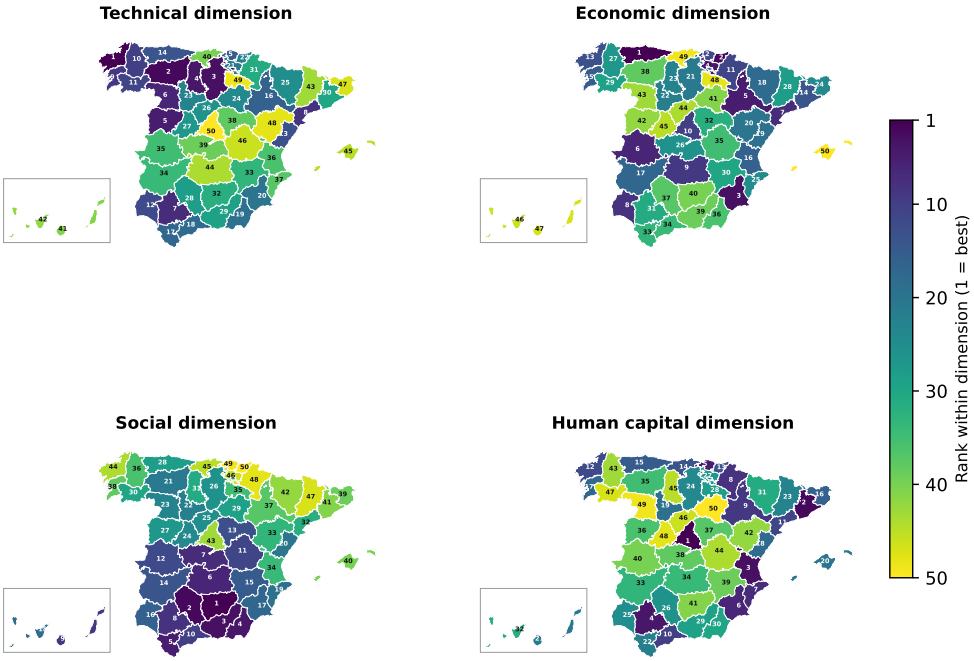


Figure 2. Provincial sub-rankings within each of the four dimensions (green-methanol scenario; 1 = best within the dimension). The social map (**bottom left**) is close to the inverse of the human-capital map (**bottom right**), the tension the overall ranking arbitrates. Produced with the open SMCE implementation (Appendix B).

3.2. Green Ammonia: The General Ranking

The ammonia ranking (Figure 3) preserves the southern, interior character of the methanol map but reorders the leading positions once the CO_2-capture criteria disappear. Sevilla now heads the ranking—driven by social need, human capital and a solid economic and technical standing—followed by Murcia (2nd) and Zaragoza (3rd), Ciudad Real (4th), Asturias (5th), Vizcaya (6th), Cádiz (7th), Almería (8th) and Málaga (MA, 9th). Removing

the carbon dependence lifts provinces rich in renewable resource and talent and demotes those whose methanol standing rested on industrial CO_2.

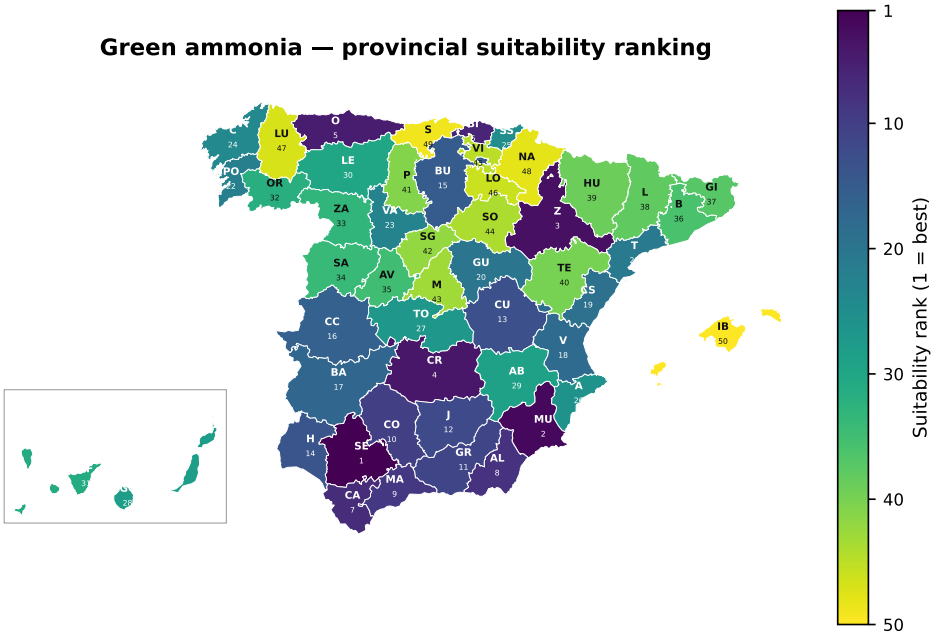


Figure 3. Green-ammonia suitability ranking of the 50 Spanish provinces (Kemeny median order; 1 = most suitable). Provinces labelled with their standard Spanish province code and rank (key in Table 2). Canary provinces shown in the inset box. Rankings from the SOCRATES model.

Dimension by Dimension

Because the economic, social and human-capital dimensions are identical to the methanol scenario, only the technical dimension changes, through the removal of C7–C8. With the industrial-carbon correction gone, technical suitability concentrates almost purely on the provinces of greatest renewable resource, available land and grid headroom. Galicia and the northern plateau now dominate—Palencia, A Coruña, Pontevedra (PO), Lugo and Ourense (OR)—as pure resource sets the order. The provinces that the carbon criteria had lifted fall back sharply: Tarragona, for instance, drops from eighth to forty-second in the technical sub-ranking. Madrid again occupies the last place.

3.3. Comparing the Two Geographies

The two maps describe almost the same territory. Nine of the ten leading provinces are common to both derivatives (Figure 4): the southern and eastern core of Murcia, Sevilla, Zaragoza, Ciudad Real, Asturias, Vizcaya, Cádiz, Almería and Córdoba is suitable whichever fuel is ultimately built. Only Huelva (methanol) and Málaga (ammonia) are exclusive to one top ten. Across all fifty provinces the two orderings correlate strongly (Spearman $\rho = 0.94$), as expected when three of the four dimensions are shared.

Where the orderings do move, the movement is concentrated and traces a single cause—the capturable-CO_2 criteria, discussed in Section 4.2. Figure 5 visualizes the shift province by province. Most provinces barely change; a handful travel a long way. Switching to ammonia lifts the renewable-rich, low-carbon provinces—A Coruña (+16), Cuenca (CU, +13), Santa Cruz de Tenerife (TF, +10) and Málaga (+9)—and demotes the carbon-anchored ones—Huelva (−13), Navarra (−10) and Alicante (−9).

Underneath this common geography, the same four logics recur as province *clusters* that summarize the model's reasoning. The high-suitability core is built from four: the *southwestern Atlantic–Andalusian arc* (Huelva, Cádiz, Sevilla), where abundant solar resource,

port access, capturable industrial CO_2 and high social need converge—which is why it leads the methanol scenario; the *Mediterranean southeast* (Murcia, Almería), pairing solar resource and port infrastructure with refinery-linked CO_2 and marked social need; the *Ebro valley* (Zaragoza), a technical–economic engine held back only by its modest social need; and the *Castilian and Andalusian interior* (Ciudad Real, Cuenca, Toledo, Jaén, Córdoba, Granada), which rises chiefly on the social term reinforced by hydrogen pipelines, the most direct expression of the just-transition lens. Three further clusters are instructive exceptions: the *industrial Cantabrian coast* (Asturias, Vizcaya) climbs on economic strength and industrial CO_2 despite low social need; *technical Galicia* (A Coruña, Pontevedra) leads the technical dimension yet falls overall, held down by low need and renewables conflict; and the *non-poor metropolitan axis* (Madrid, Barcelona (B)) is relegated to the bottom, strong in human capital but technically unviable and low in need. The full 50-province orderings are given in Table 2.

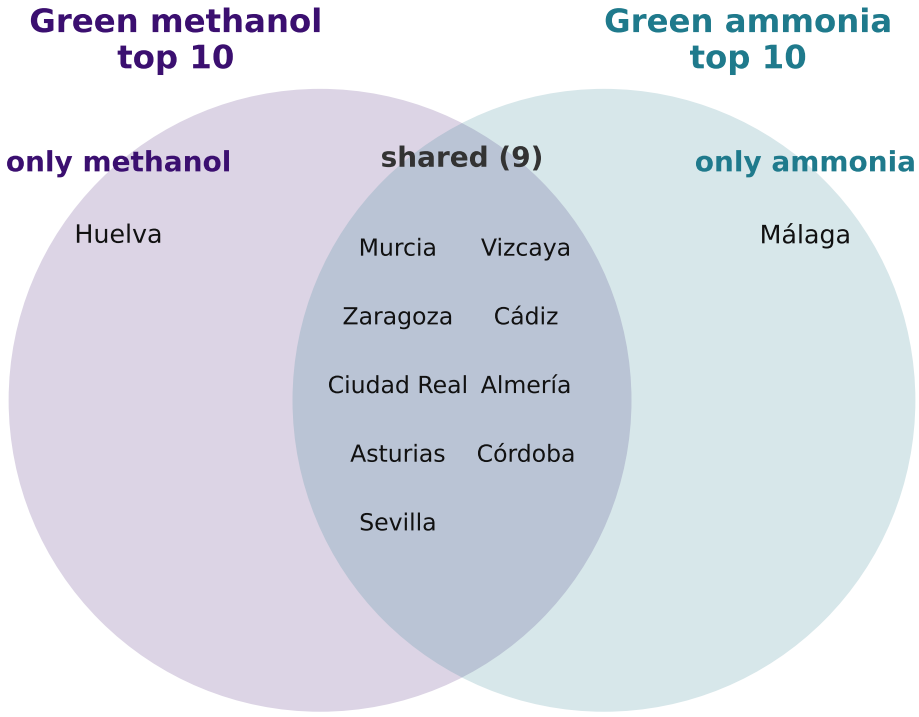


Figure 4. Overlap of the two top-ten sets. Nine provinces are suitable for both derivatives; only Huelva (methanol) and Málaga (ammonia) are exclusive to one scenario.

3.4. Robustness: Local and Global Weight Sensitivity

Because the dimension weights are the study's central normative choice, we probe their effect with two complementary analyses. A *local* sensitivity analysis, in the sense of Munda [25], perturbs one weight at a time: the weight of a single dimension is raised to 50% of the total while the other three are held equal to one another and share the remaining 50%; recomputing the ranking then shows how far emphasizing that one dimension moves the result. A *global* analysis instead varies all four weights simultaneously by Monte-Carlo sampling, mapping the ranking over the whole weight space rather than along single axes.

The local analysis (Table 3) delivers a clear message. Emphasizing the *social* dimension barely disturbs the ranking (ρ = 0.87 methanol, 0.81 ammonia)—unsurprisingly, since it already carries the largest weight, so raising it to 50% is a small move on an already social-led map. Emphasizing *human capital*, by contrast, reshapes the ranking the most (ρ = 0.52 and 0.43) and installs Madrid as leader: it is the near-inverse of the social map, so shifting weight onto it reverses the geography. Emphasizing the economic dimension brings

the industrial north (Asturias) to the top. The ranking, in other words, is most sensitive to the dimensions that pull *against* social need.

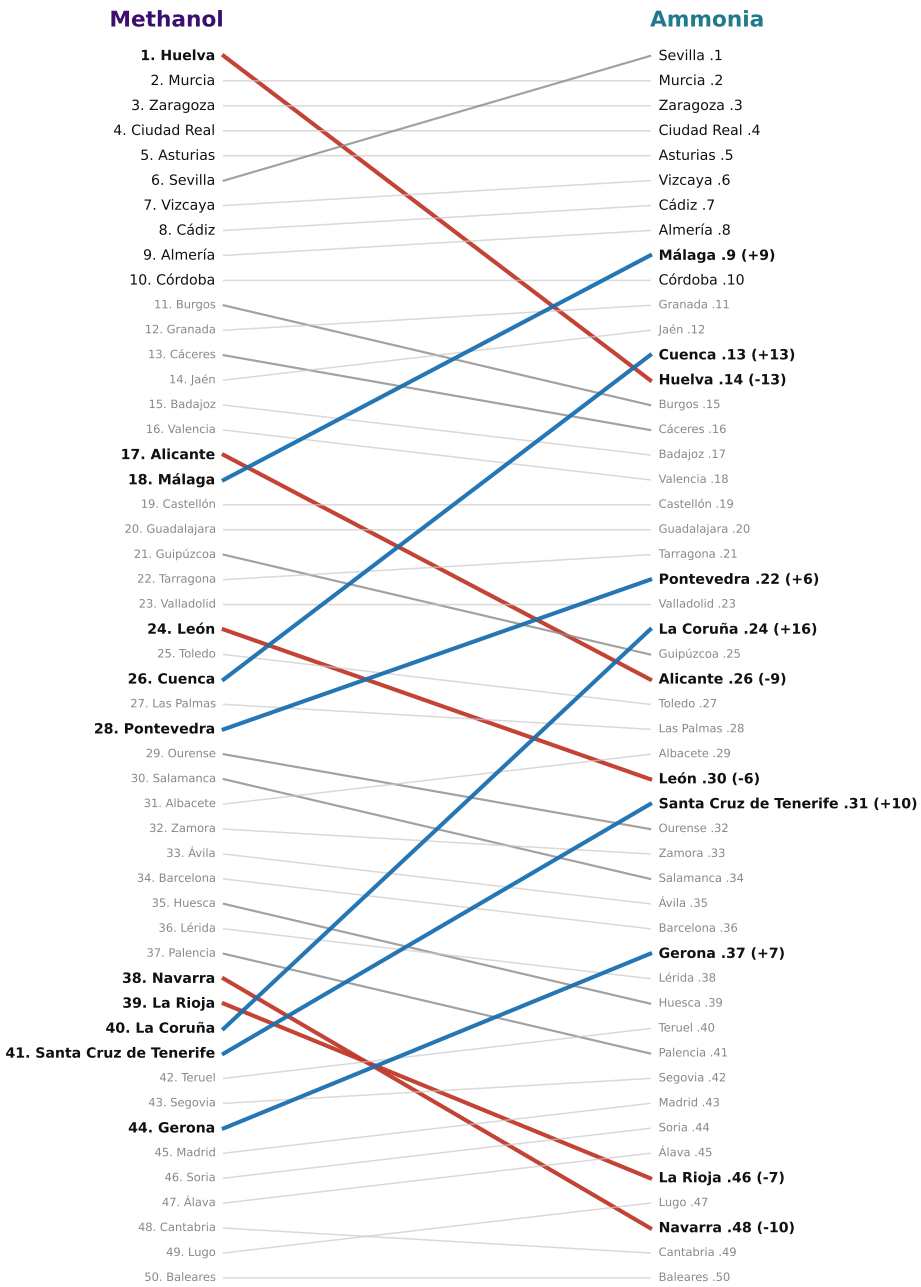


Figure 5. Rank shift of every province from the methanol to the ammonia scenario (rank 1 at the top). Blue lines rise for ammonia, red lines fall; grey lines are broadly stable. Only movements of six positions or more are labelled with their size. The full orderings are in Table 2.

The global analysis explored the dimension-weight space by Monte-Carlo sampling, with no dimension allowed to exceed 50%, recording for each province the distribution of ranks it attains. Dimension-weight vectors are drawn from a symmetric Dirichlet over the simplex, each dimension capped at 0.5 by rejection sampling; $M = 1500$ vectors are drawn per scenario. Each draw yields a single Kemeny order (the ordering that maximizes pairwise agreement; where the search finds equally optimal orders, one is retained), so no weight vector is discarded on account of ties; the rejection step applies only to the per-dimension cap. Robustness is judged by each province's median rank *and* its 5–95% band,

a province being weight-robust when that band remains in the upper group; convergence is reached by $M \approx 250$. It separates structurally robust positions from weight-dependent ones, and its conclusion qualifies the rankings above in an important way.

Table 3. Local weight sensitivity. Each row raises one dimension's weight to 50% (the other three held equal) and reports the Spearman rank correlation between the resulting ranking and the original, adopted-weight ranking—that is, how much the order changes: $\rho = 1$ would mean it is unchanged, and lower values mean a larger reordering. The leader each perturbation produces is shown in brackets. Computed with the open implementation (Appendix B).

Dimension Raised to 50%	Methanol	Ammonia
Technical	0.78 (Asturias)	0.73 (A Coruña)
Economic	0.64 (Asturias)	0.55 (Asturias)
Social	0.87 (Murcia)	0.81 (Jaén)
Human capital	**0.52 (Madrid)**	**0.43 (Madrid)**

Two findings stand out. First, a small set of provinces stays near the top under almost any weighting. Murcia is the most stable of all, with a median rank of 2 and a very narrow band in methanol and ammonia alike; Asturias and Sevilla sit close behind, and Zaragoza keeps a high median though with a wider band. These are the weight-robust sites—strong whatever derivative is ultimately chosen and whatever reasonable weighting is adopted. Second, the scenario leaders are the least stable of all. Huelva tops the methanol ranking under the adopted weighting, yet across the weight space its median rank falls to about eleven; Sevilla plays the same fragile role for ammonia. Figure 6 shows the contrast at a glance: Murcia holds a tight band near the top, whereas Huelva—the fixed-weight methanol leader—sits at a median well below first with a wide band. The operational reading follows. The robust recommendation is not a single winning territory but the stable core around Murcia; each ranking's specific head should be read as a result amplified by the social priority, not as an unconditional designation.

The mechanism is legible in the model itself. How stable a province is under re-weighting depends on how evenly its strengths are spread across the four dimensions. Murcia scores well on all of them at once—economy, human capital and social need—so no redistribution of weight dislodges it, and its band stays narrow. Huelva's first place, by contrast, rests on a specific combination: the high social need and the capturable industrial CO_2 that the adopted weighting happens to reward together. As soon as weight shifts away from that combination its advantage erodes, which is why its band is wide and its median far from first. In short, balanced profiles are robust and concentrated ones are not, and the non-compensatory aggregation makes that difference visible rather than averaging it away.

Three further checks confirm that this picture does not hinge on the specific design of the global analysis. First, a convergence check confirms this (Figure 7): the median ranks settle by about $M = 250$ draws and are flat up to the $M = 1500$ used here—for example Murcia holds median rank 2 (5–95% band 1–4), Sevilla 5 (1–10), Asturias 4 (1–11) and Huelva 11 (5–20) from $M \approx 250$ onward. Second, the 50% cap is not what drives the result: repeating the analysis under caps of 0.4, 0.6 and no cap leaves the weight-robust core essentially unchanged (across all four settings Murcia holds median rank 2, Sevilla 5, and Madrid stays at 22–24). Third, and addressing the assumption that criteria are equally weighted within each dimension, we extended the Monte-Carlo sampling so that the criterion weights inside every dimension also vary (drawing them from the criterion simplex). The core persists under this richer perturbation as well: Murcia holds a median rank of 3–4 with a tight band, and Sevilla, Asturias and Córdoba remain in the upper group, so the finding does not depend on the equal-within-dimension assumption.

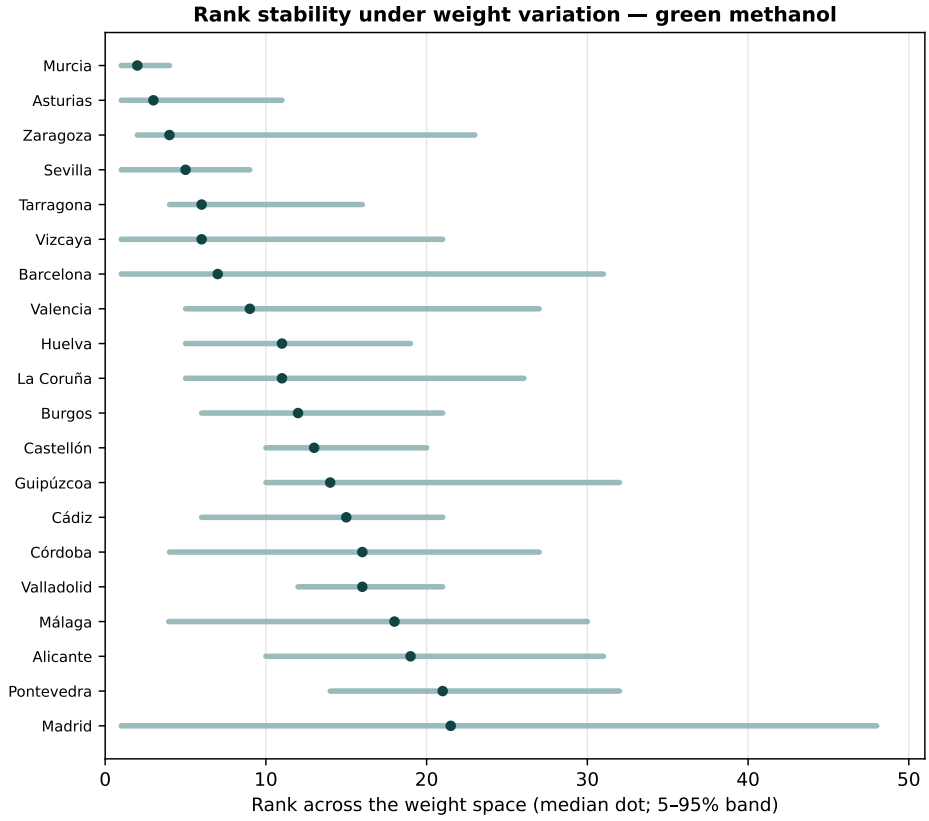


Figure 6. Rank stability of the top provinces (green methanol) across a Monte-Carlo sample of dimension weightings (no dimension exceeding 50%). Dot = median rank; bar = 5th–95th percentile band. Murcia is the weight-robust core; Huelva's fixed-weight lead dilutes across the weight space. Produced with the open SMCE implementation (Appendix B).

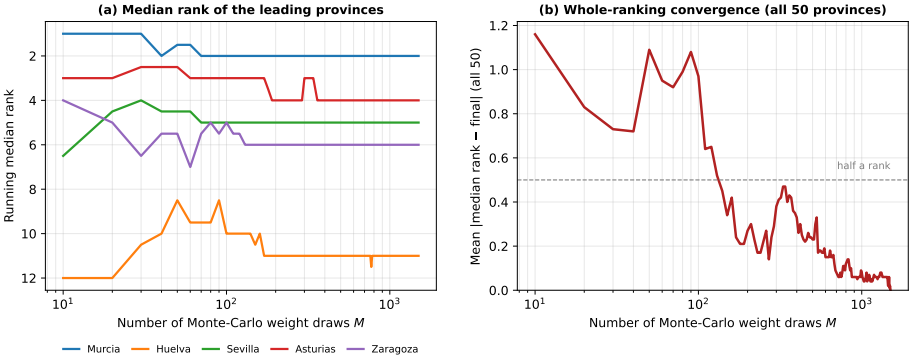


Figure 7. Convergence of the global weight-sensitivity analysis (logarithmic in M). (**a**) Running median rank of the leading provinces (green methanol) against the number of Monte-Carlo weight draws M; the medians stabilize by about $M = 250$ and are flat up to the $M = 1500$ used in the paper. (**b**) Whole-ranking convergence across all 50 provinces: the mean absolute difference between each province's running median rank and its final ($M = 1500$) value, which falls below half a rank by $M \approx 140$ and continues toward zero. Produced with the open SMCE implementation (Appendix B).

3.5. Robustness to the Criteria Set

The weights are not the only modelling choice open to question; the selection of criteria is another. Our open re-implementation of the model (Appendix B) lets us probe this directly, by re-running the analysis under systematic changes to the criteria set. Several checks, reported below, bound how much the criteria definition matters; the more consequential choice—the dimension weighting—is isolated separately in Section 3.6.

First, the criteria are largely non-redundant. Across all 171 criterion pairs the strongest Spearman correlation is 0.88 and the mean is 0.29, with only three pairs above 0.8; those three reflect real features of Spanish geography—the sunniest provinces are also the most water-stressed and among the highest in unemployment—rather than duplicated measurement. The one exception is the human-capital dimension, whose four indicators are appreciably intercorrelated (mean $|\rho| = 0.61$) because they all proxy the same underlying factor: the concentration of qualified, working-age population in urban provinces. That redundancy is benign here—human capital carries the smallest weight (15%), and the two checks that follow show that neither dropping any of its criteria nor removing the dimension as a whole changes the ranking materially—but it marks the natural place to consolidate criteria in a future refinement. Second, dropping any single criterion barely moves the result: across the nineteen single-criterion removals the median Spearman correlation with the full ranking is 0.96, and at least six of the top ten provinces survive every removal. No individual criterion drives the outcome, but the criteria that matter most are telling. The five whose removal moves the ranking furthest (Table 4) are four social criteria and one economic one; removing any technical criterion—solar resource included ($\rho = 0.94$)—changes almost nothing. Influence tracks the social dimension, not the physical resource base.

The influential criteria being social, we also checked that the result does not hinge on how the most contestable of them is coded: re-expressing the renewables-conflict index C15 under alternative definitions—including a severe binary present/absent recoding that correlates only moderately with the graded index (Spearman $\rho = 0.42$ as a criterion)—leaves the overall ranking essentially unchanged ($\rho \geq 0.86$ against the baseline, leading province unchanged), so the geography does not depend on the coding of the conflict criterion; the alternative constructions and their outputs are included in the released repository.

Table 4. The five most influential single criteria (green methanol). Each row removes one criterion and reports the Spearman rank correlation between the resulting ranking and the original ranking; a lower value means removing that criterion changes the order more ($\rho = 1$ would leave it unchanged). Four of the five are social criteria; the most influential technical criterion (solar resource) gives $\rho = 0.94$. Open implementation (Appendix B).

Criterion Removed	Dimension	Spearman ρ
C13 Unemployment rate	Social	0.84
C15 Renewables conflict	Social	0.85
C10 Renewable H_2 projects	Economic	0.87
C12 Social vulnerability	Social	0.87
C14 Depopulation index	Social	0.88

Third, we tested the spatial aggregation directly. Three criteria (grid capacity C5, biogenic CO_2 C8, and the regionally adjusted AROPE C12) are available only at the autonomous-community level and were apportioned to provinces, which imposes within-community uniformity. Removing all three and recomputing changes the ranking only modestly (Spearman $\rho = 0.83$ for methanol and 0.85 for ammonia, with five of the top ten retained in each scenario); the main visible effect is a shift of the single leader (Huelva to Murcia), so the apportionment shapes the head of the ranking more than its overall structure.

Fourth, a distinct question is one of *specification* rather than robustness: how the count-based criteria should be scaled. Four criteria enter as absolute counts or flows—renewable-hydrogen projects (C10), hydrogen-sector FDI (C11), industrial VET centres (C18) and engineering programmes (C19)—which, as a reviewer notes, mechanically favour larger provinces. This is a considered choice rather than an oversight. Absolute counts and per-capita rates measure different things: the former captures *agglomeration and installed capacity*, the latter *intensity relative to population*. For deciding where an industry can be

built and staffed, the relevant quantity is the absolute capacity a territory offers—the size of its project ecosystem, the investment it actually attracts, and the absolute supply of vocational and engineering graduates within reach—not that capacity per head; a single project in a sparsely populated province is not evidence of an industrial cluster. We therefore adopt the absolute encoding as the measure appropriate to a capacity criterion. The case is strongest for the two economic criteria, where the project ecosystem (C10) and the investment a province attracts (C11) are inherently agglomeration measures; it is weaker for the two education-supply criteria (C18, C19), where a per-working-age rate carries a more legitimate reading, and these are the criteria we would normalize first in a refinement. Re-expressing the four criteria in normalized form (C10 and C11 per capita; C18 and C19 per working-age population) answers a different question and, as one would expect, produces a different ordering (Spearman $\rho = 0.65$ for methanol and 0.60 for ammonia relative to the absolute encoding): the leader becomes Guadalajara and sparsely populated provinces (Palencia, Soria) rise, because a single project or programme looms large per inhabitant. Neither encoding is inherently neutral—the absolute favours large provinces, the per-capita over-rewards very small ones—and the size-aware ideal (for example, committed electrolyzer capacity rather than a project count) lies between them and is not available at provincial resolution; we report the per-capita variant for comparison. Crucially, this specification choice touches only the economic and human-capital dimensions (weights 20% and 15%): the social dimension that drives the geography is already expressed in rates (AROPE, unemployment, depopulation and the conflict index), so the paper's central finding—that an explicit social weighting yields a geography distinct from the techno-economic optimum—holds under either encoding, with the high-need southern and interior provinces (Córdoba, Ciudad Real, Almería, Granada, Jaén, Cádiz) prominent in both.

A further check probes the capturable-CO_2 assumptions that underlie the methanol-specific criteria. Under a conservative treatment of capturable CO_2—halving the weight of the industrial criterion C7—the methanol ranking barely moves ($\rho = 0.97$) and Huelva remains first; removing industrial CO_2 altogether and keeping only the purer biogenic stream lowers Huelva from first to ninth (still within the top ten) while leaving the robust social core unchanged ($\rho = 0.91$), confirming that Huelva's lead is partly carbon-anchored but the upper tier is not an artefact of the most optimistic capture assumption.

The count of mature projects (C10) can also be probed on its own. Because a project count weights initiatives of very different size equally, we removed C10 alone: the overall ranking stays fairly stable (Spearman $\rho = 0.87$ methanol, 0.95 ammonia), but Huelva—the methanol leader, which hosts the most mature projects—falls from first to seventeenth, while the weight-robust core is essentially unchanged and Murcia becomes the leader. The project count therefore shapes which province heads the ranking more than it shapes the overall social geography; a capacity-weighted version is left to future work, as comparable provincial capacity figures are not yet available.

We also examined path-dependence in the economic criteria, since project counts and sector investment can reflect past deployment as much as future potential. Removing the deployment-momentum criteria (C10, C11) reorders the ranking appreciably ($\rho = 0.58$ methanol, 0.63 ammonia): these criteria are a genuine pillar, so the specific leaders depend on them. The shift, however, is toward high-need rural interior provinces (Palencia, Burgos, Guadalajara rise; Jaén, Córdoba, Sevilla remain), so the central social tilt is preserved rather than reversed.

A distinct question concerns minimum feasibility: whether the aggregation should impose a floor on critical criteria. The non-compensatory rule prevents a large advantage from buying back a large deficit, but it does not impose a minimum standard on any single criterion; consequently a weight-robust province may still face a binding local constraint—for

example Murcia, which ranks highly yet is among the most water-stressed, or Zaragoza, with little spare grid capacity. We do not add a veto at this screening stage: minimum-feasibility thresholds on water, grid or safety belong to the site-specific assessment that must follow a strategic screening.

Finally, to make the effect of the non-compensatory rule itself transparent, we re-ranked the provinces with two classical *compensatory* methods—a weighted sum and TOPSIS—using the same weights and criterion directions. The compensatory geography is markedly different: TOPSIS places Madrid first in both scenarios (from 45th under the Kemeny rule), with Barcelona, Vizcaya and Álava climbing sharply, and correlates only weakly with the adopted ranking (Spearman $\rho \approx 0.35$–0.50); the weighted sum is intermediate ($\rho \approx 0.70$–0.75) but likewise lifts the wealthy, low-need provinces. This confirms that it is the non-compensatory aggregation—not any artefact of the data—that prevents a strong techno-economic or human-capital score from buying back a severe social deficit, and so keeps the metropolitan cores from displacing high-need provinces.

3.6. The Weight of the Social Dimension

The single most consequential check is to remove each *dimension* in turn—redistributing its weight over the other three—and recompute (Table 5). Removing the technical, economic or human-capital dimension leaves the ranking largely intact (ρ between 0.80 and 0.94). Removing the *social* dimension is the single change that reshapes it ($\rho = 0.60$ methanol, 0.46 ammonia): the wealthy, low-need provinces—Vizcaya, Zaragoza, Barcelona—return to the top and the map reverts to the conventional techno-economic geography. This is the mirror image of the local sensitivity of Section 3.4: the social dimension changes the ranking most when *removed* yet least when further *emphasized*, precisely because it already anchors the adopted weighting. One modelling choice governs the result: the deliberate decision to weight social need—the paper's contribution, whose consequences the analysis quantifies exactly. The ranking is robust in the proper sense, surviving the weight perturbations, the cap and the removal of individual or apportioned criteria. The separate question of how the count-based criteria are scaled—absolute capacity versus per-head intensity—is one of *specification* rather than robustness, and is treated in Section 3.5.

Table 5. Leave-one-dimension-out robustness. Each row removes one dimension (its weight redistributed over the remaining three) and reports the Spearman rank correlation between the resulting ranking and the original ranking—i.e., how much the order changes, with $\rho = 1$ meaning unchanged. Low values mean the dimension matters most; only the social dimension materially reshapes either ranking.

Dimension Removed	Methanol	Ammonia
Technical	0.94	0.93
Economic	0.80	0.82
Human capital	0.83	0.87
Social	**0.60**	**0.46**

4. Discussion

4.1. The Dimensions Pull Against Each Other

The results of Section 3 carry an argument that goes beyond the two maps. Their central lesson is that the four dimensions are not merely different but partly *opposed*: the provinces that score best on the economic and human-capital dimensions—the wealthy north and the metropolitan cores—are among the worst on social need, and vice versa. The near-inversion of the social and human-capital maps (Figure 2) is the clearest expression of this tension, and the robustness analysis turns it into a quantitative claim. The leave-one-dimension-out

test (Table 5) shows that removing the social dimension is the one change that reshapes the ranking, reverting it to the conventional techno-economic geography; the local sensitivity (Table 3) shows the same thing from the other side, since emphasizing human capital reverses the map and installs Madrid as leader. In other words, whether social need is weighted heavily is not a detail but the decision that determines the outcome.

It is worth being precise about what a high social-need score signals: priority for productive transformation under a distributive-justice lens, not that a province is technically most suitable or that the benefits of siting will automatically accrue. Directing large, potentially burdensome infrastructure toward disadvantaged territories also carries its own equity risk—of adding environmental burdens where the capacity to contest them is weakest—which a distributive ranking does not resolve and which procedural-justice and local-participation mechanisms, outside the scope of this model, must address.

This matters because the siting literature has largely treated the social dimension as a constraint or an afterthought, when it is present at all, and has concentrated on the techno-economic optimum [16,18]. Our results suggest that this omission is not neutral: because the dimensions are opposed, a model that under-weights social need does not merely lose some nuance, it selects a systematically different set of territories—the already-advantaged ones. Making social need an explicit, high-weight objective is therefore what gives the exercise its distinctive geography, and the robustness checks confirm that this deliberate choice, rather than the weighting or the incidental removal of individual criteria, is what drives the result. The one modelling choice that also moves the ranking, the scaling of the count-based criteria (absolute versus per-capita), is a question of *specification* rather than robustness (Section 3.5) and leaves the rate-based social geography intact.

4.2. The CO_2 Effect: Winners and Losers

Because the two scenarios differ only in criteria C7–C8, the differences between the rankings can be attributed cleanly to the methanol pathway's dependence on captured CO_2. That dependence acts as a corrective on the pure renewable-resource picture. On the methanol side it lifts industrial, port-connected provinces with access to concentrated CO_2 sources. Huelva, with its chemical hub, and Tarragona, with its petrochemical complex, are the clearest cases, and the industrial north around Asturias is reinforced too—all provinces that a solar-and-wind map alone would overlook. Removing the requirement, as in the ammonia scenario, demotes exactly these carbon-anchored provinces and elevates those that combine renewable resource, economic strength and talent, bringing Sevilla to the top. Figure 8 makes the mechanism visible. Huelva, the carbon-anchored methanol leader, falls the furthest—thirteen places—once the CO_2 criteria are removed. The provinces that rise the most never depended on industrial carbon and are instead strong in renewable resource or high in need: A Coruña and the rest of Galicia, Cuenca and Málaga. The central comparative finding is thus that feedstock, not resource, is what distinguishes where the two derivatives should be made.

Two qualifications temper this reading. First, that capturable CO_2 is the *only* differentiator holds within the present analytical framework, because it is the only criterion the model allows to differ between scenarios; in reality the two chains also diverge in safety, storage and transport, product market and demand, technology maturity, water use and regulation, none of which enters this siting model. Second, treating industrial CO_2 as a positive siting attribute conflates two things that should be kept apart: the *availability* of concentrated feedstock and the *environmental acceptability* of building new capture-dependent plants next to already carbon-intensive industry. A high C7 score signals the former, not the latter. The durability and regulatory eligibility of the sources also differ, and Delegated Regulation (EU) 2023/1185 makes the timeline explicit for a fuel to count as an RFNBO: CO_2 captured

from activities covered by the EU ETS qualifies only if it has already borne its upstream carbon price; CO_2 from fossil-fuel electricity generation is eligible until the end of 2035 and CO_2 from fossil-fuel combustion in industry until the end of 2040; from 2041 onward only biogenic CO_2 meeting the sustainability criteria, CO_2 captured directly from the air, CO_2 from geological sources, and CO_2 from the combustion of recycled-carbon or renewable fuels remain admissible. A province's industrial-carbon endowment is therefore a time-limited, source-dependent advantage—most of the fossil-industrial CO_2 that lifts a province today loses eligibility after 2040—whereas its biogenic CO_2 (C8) is durable, a distinction the ranking does not weigh but that matters for long-run siting.

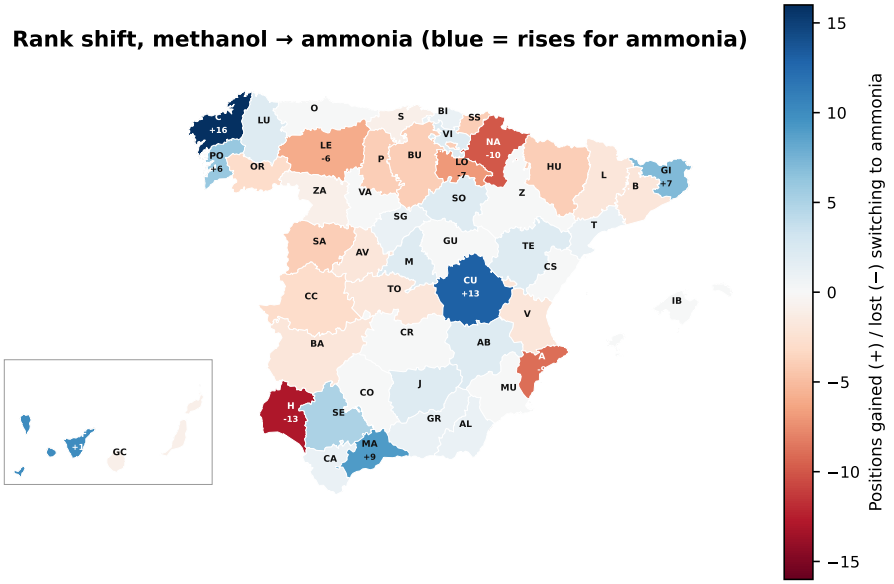


Figure 8. Change in provincial rank when switching from green methanol to green ammonia (positions gained in blue, lost in red). Huelva, the carbon-anchored methanol leader, falls the furthest (−13) once capturable CO_2 is removed, while provinces strong in renewable resource or high in need rise the most (A Coruña +16, Cuenca +13, Málaga +9). Provinces labelled with their standard Spanish province code (key in Table 2). Change computed from the two SOCRATES rankings in Table 2.

4.3. Four Provinces, Four Logics

The same tension is visible province by province, and four cases read almost as a typology. *Huelva* has a balanced profile, with solid positions across all four dimensions and no marked weakness. That balance, plus its carbon anchor, carries it to the top for methanol. When the CO_2 criteria vanish it loses the very factor that set it apart, and falls back. *A Coruña* is its near-mirror image: at the very top of the technical dimension, but lagging on the social one. It sits 40th for methanol, held down by low social need and by conflict around renewables. For ammonia it climbs to 24th—the single largest gain between the two derivatives—as the removal of the carbon anchor lets its renewable resource speak. *Murcia* traces a broad, balanced diamond, strong in economy, human capital and social need at once, and that distributed solidity keeps it near the top of both scenarios and robust to re-weighting. *Madrid*, by contrast, concentrates all its value in a single vertex—human capital—and collapses on the others, above all the technical, so it sits low in both scenarios. Together they make the point plain: the model rewards not any one strength in isolation but the way strengths and needs are distributed across a territory.

4.4. Implications for Industrial Policy and a Just Transition

Read as guidance rather than prediction, the results point to a clear industrial strategy in a just-transition key. Operationally, such a ranking is best used not as an automatic site

selector but as a prioritization layer by the bodies that already steer this transition: the Ministry for the Ecological Transition (MITECO) and IDAE in allocating PERTE-ERHA and hydrogen-valley support, the autonomous communities in regional energy and industrial planning and permitting, port authorities for bunkering and export infrastructure, and the just-transition boards (*mesas de transición justa*) that negotiate territorial agreements—each of which could weigh these provincial priorities against the site-specific constraints the model does not capture. The most concrete lever is public funding: in Spain, subsidies for renewable hydrogen and its derivatives are channelled largely through IDAE (which has awarded on the order of EUR 3 billion to date), and projects are currently selected on technical requirements and offtake commitments, with no explicit social criterion. A socially weighted ranking such as this one is precisely the kind of instrument that could enter that allocation, helping ensure that publicly funded projects reflect territorial social need rather than techno-economic merit alone. The existence of a weight-robust core—ranking highly independently of derivative and weighting—offers planners a stable foundation on which to concentrate the first wave of deployment, while the weight-sensitive scenario leaders counsel prudence: a siting decision should rest on the stable group, not on a single province whose lead may be an artefact of the chosen weights. The comparative reading further suggests complementarity rather than competition between derivatives. Methanol finds its natural fit where capturable carbon and industrial fabric coincide; ammonia where renewable resource and talent concentrate. This complementarity has a practical value under uncertainty. It is still unclear which fuel will dominate maritime decarbonization—methanol and ammonia each have serious backers, and the likeliest outcome is that both coexist, serving different vessel classes and routes. A province suitable for only one derivative is therefore a bet on that fuel winning; the shared robust core identified here—provinces that rank near the top for *both*, Murcia above all—is instead a hedge, a place where an early commitment pays off whichever pathway the market ultimately favours. Concentrating the first wave of deployment there is the strategy most robust to the choice of weights. In every case the weight of the social dimension anchors activity in the southern and interior provinces of greatest territorial need, aligning the siting of renewable-hydrogen production with the goals of territorial cohesion and the demographic challenge—so that siting *could* act as an instrument of regional development. We frame this as a policy hypothesis rather than a demonstrated outcome: the model ranks provinces by just-transition priority, but it does not estimate the employment, demographic or welfare effects that would determine whether such benefits actually materialize.

A further caution concerns what the ranking does and does not establish. A high social-priority score identifies a province where productive transformation is most needed; it is not a finding that the province is a suitable or safe host for a specific, potentially hazardous industrial installation, which depends on local land, grid, water and safety conditions assessed at a finer scale. Directing such infrastructure toward disadvantaged territories also carries its own equity risk: our framework addresses distributive justice—where need is greatest—whereas procedural justice, community consent and the fair distribution of local environmental burdens are not captured by an indicator ranking and must govern the subsequent, site-specific stage. The SMCE equity component that would formalize stakeholder appraisal is deliberately not applied at this screening stage.

It is worth noting that the weight-robust core the model identifies coincides closely with where Spanish policy is already acting, which offers a measure of external *consistency* rather than independent validation. The country's "hydrogen valleys" cluster in Cartagena (Murcia), Puertollano (Ciudad Real), the Andalusian coast and Asturias, and several just-transition territories overlap with the same interior and southern provinces (The renewable-hydrogen "valleys" funded under the PERTE ERHA [46] and the territories of the EU

Just Transition Fund [47]). This correspondence should be read with care, and not as an independent test of the model, for two reasons: the hydrogen valleys were themselves selected through policy and investment processes rather than sampled independently, and two of our economic criteria (C10, mature hydrogen projects, and C11, hydrogen-sector FDI) already embed existing hydrogen activity, so part of the overlap is endogenous to the model. With that caveat, the fact that a socially weighted model run on independent public data recovers much of the geography policy has selected on other grounds offers qualitative, partial corroboration; and where model and policy diverge, the divergence is itself informative, flagging provinces of high need and real potential that current instruments may be under-serving.

Figure 9 makes this comparison explicit, classifying each province by whether its social-priority rank and its current renewable-hydrogen activity (criterion C10, from the IIT-ICAI hydrogen observatory and the AeH2 project census [48]) agree. The bulk of the socially prioritized core already coincides with concentrated activity—Murcia, Huelva, Zaragoza, Sevilla, Asturias, Cádiz and Almería all combine a high rank with several projects (green)—which is the source of the qualitative agreement above. The interesting cases are the mismatches: provinces such as Jaén rank high on social priority yet host very few projects (red; candidates the framework flags as under-served), whereas provinces such as Madrid, Barcelona and Navarra concentrate current activity despite a low social-priority rank (blue). The framework thus does not merely reproduce the existing map of investment; it reweights it toward territorial need.

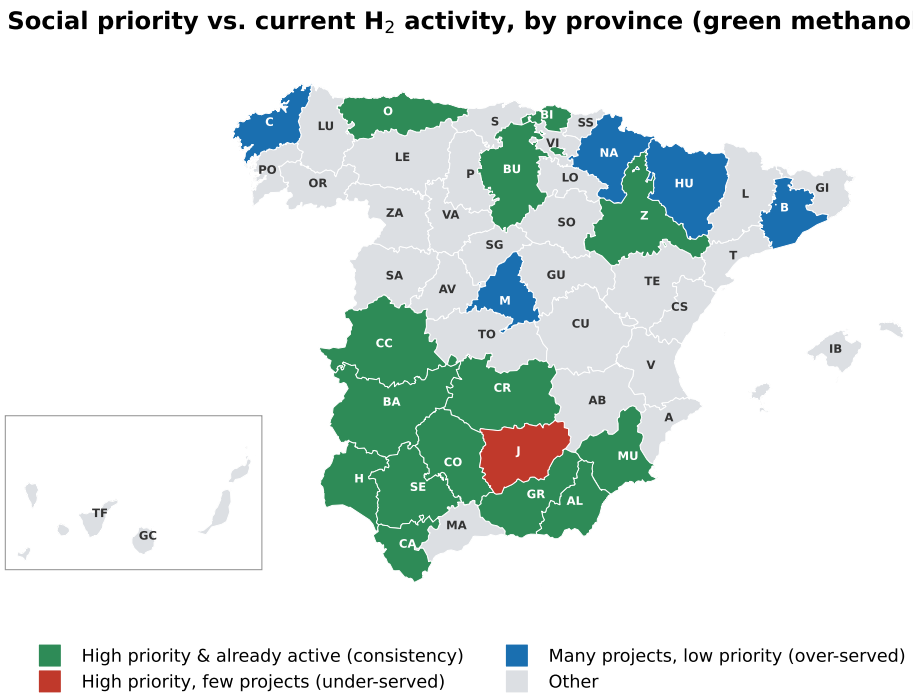


Figure 9. Social priority versus current renewable-hydrogen activity, by province (green methanol). Each province is coloured by the match between its social-priority rank and its number of mature hydrogen projects (criterion C10; IIT-ICAI H_2 Observatory and AeH2 census [48]): green, high priority (rank ≤ 15) and already active (≥3 projects); red, high priority but few projects (≤2), i.e., under-served; blue, many projects (≥4) but low priority (rank ≥ 26), i.e., over-served; grey, other. Province codes as in Table 2.

4.5. Beyond Fixed Weights: Balance as a Result

A further contribution is methodological, and the sensitivity analysis is where it shows. Most siting studies evaluate a *single* configuration of weights—often elicited by AHP from

an expert panel—and report the ranking it produces. That procedure cannot distinguish a province that ranks highly because it is genuinely balanced across dimensions from one that ranks highly only because the chosen weights happen to favour its single strength. Our results show the distinction is real and consequential: under local and global re-weighting, some provinces (Murcia above all) hold their position because their strengths are evenly distributed, while the fixed-weight scenario leaders (Huelva, Sevilla) rest on a specific combination and disperse as soon as weight moves away from it. Reading robustness as a result in its own right—not a diagnostic afterthought—lets the method recommend the balanced, weight-robust territories rather than the artefacts of one weighting.

This has a direct bearing on the limits of the compensatory, fixed-weight tradition. Under an AHP weighting that assigns, say, 0.9 to solar resource and 0.1 to social need, a province that is excellent on radiation but severely deprived would outrank one that is merely good on both—and the single-configuration analysis would never reveal that the "winner" is fragile while the runner-up is robust. The non-compensatory Kemeny aggregation prevents a strong score on one dimension from simply buying off a deficit on another, and the sensitivity sweep exposes which positions survive re-weighting. The approach also sidesteps a practical weakness of AHP: it needs no pairwise expert survey, so it is cheaper to run and more transparent to replicate, with the weights stated explicitly as the normative choices they are rather than laundered through an elicitation exercise.

The same openness turns the analysis into a tool for examining its own assumptions, which we regard as a feature rather than a defect. Because the model and its data are released as an executable re-implementation, any such question can be answered by re-running it, and the answer is reported whatever it is. This is how we established where the ranking is stable—across weightings, caps and single-criterion removals—and how we could separate genuine robustness from questions of *specification*, such as whether the count-based criteria are scaled in absolute or per-capita terms (Section 3.5). A framework that exposes which of its results are structural, which depend on the weighting, and which depend on how a criterion is defined is more useful for policy than one that reports a single confident ranking, because it tells a planner exactly which parts of the result to trust and which are conditional on a modelling choice.

Seen this way, the study is itself a contribution to the practice of sustainability. It offers a transparent, reproducible framework that *quantifies and makes monitorable* the social and territorial dimension of the energy transition—a dimension usually left implicit in techno-economic siting—and integrates it with the technical, economic and human-capital dimensions within a single evaluation. By turning distributive and territorial-cohesion objectives into explicit, weighted criteria whose influence can be audited, the framework supports the design and monitoring of policies under the European Green Deal and the Just Transition Fund, and is portable to other regions, molecules and priority sets. In this sense the paper contributes not only a result for Spain but an instrument for defining, measuring and tracking the social sustainability of industrial-siting decisions.

4.6. Comparison with Prior Work

These results both confirm and extend the existing siting literature. They confirm it in that technical and economic endowments—solar resource, water, port and industrial access—remain decisive, reproducing the kind of ranking a recent GIS–AHP or MCDA siting study [49] would yield when those criteria dominate [16,18,19,22]. They extend it along the three lines set out in Section 1. First, by promoting social need from a constraint to an explicit, high-weight objective, we obtain a materially different geography—one shifted toward the south and interior—rather than a marginal re-ordering of the techno-economic optimum. Second, the non-compensatory Kemeny aggregation prevents a strong

techno-economic score from masking a severe social deficit, in contrast to the compensatory weighted-sum and AHP schemes that prevail in this literature [15]; the price, discussed below, is that the method orders rather than scores provinces. Third, by evaluating methanol and ammonia within one framework we isolate capturable CO_2 as the single feedstock that reshapes the map—a comparative result absent from single-technology studies. Set against the three strands this work draws on, its added value is specific rather than a matter of novel combination. Relative to GIS- and MCDA-based hydrogen and power-to-X siting studies, which rank locations by technical and economic suitability [17,20,21], the value added is to carry territorial social need as an explicit, high-weight objective rather than a post-hoc filter. Relative to the wider social-sustainability-indicator MCDA tradition [35,36], it is to aggregate non-compensatorily, so that a social deficit cannot be averaged away by techno-economic strength. Relative to the energy- and distributive-justice siting literature [9,11,12], which argues *why* need should count but seldom operationalizes it spatially, it is to turn that principle into a reproducible, auditable provincial ranking evaluated for two derivatives at once. Each element is well known; what the paper contributes is what each gains when put to work on this siting problem. In doing so the paper operationalizes the "spatially just" transition that the energy-justice literature calls for but seldom connects to concrete siting tools [23,24]. It also carries the SMCE tradition in renewable-energy planning in Spain [26–28] beyond single installations, to a national, comparative, derivative-level assessment.

4.7. Limitations

Several limitations qualify the conclusions. First, the dimension weighting—in particular the high social weight—and the selection and encoding of criteria are normative modelling choices that condition the results. We do not claim to remove that subjectivity, and our robustness analysis draws an important distinction here. The result is stable to the *weighting*: it survives large changes in the dimension weights, the within-dimension criterion weights, the 50% cap and the removal of any single criterion or of the apportioned criteria (Sections 3.4–3.6), with one deliberate exception—the social dimension, whose removal reverts the result, which is the paper's very point. Separately, the ranking responds to the *specification* of the four count-based criteria (C10, C11, C18, C19)—absolute counts versus per-capita rates ($\rho = 0.65/0.60$)—which is a question of what to measure rather than of stability (Section 3.5); neither encoding is neutral, the size-appropriate measure is unavailable at provincial resolution, and the rate-based social geography that drives the result is unchanged either way. Whether the criteria are the *best* available remains, likewise, an open modelling choice we document rather than treat as settled. Second, the outranking method orders provinces without measuring the magnitude of the differences between them, and its non-compensatory nature means a strength spread across several dimensions can outweigh a severe deficit in one. A low-social-need province such as Vizcaya can thus still rank highly (sixth for ammonia) despite closing the social dimension, so rankings must always be read together with the sensitivity analysis. Third, spatial granularity enters at two levels. Below the provincial scale, the analysis masks intra-provincial heterogeneity—local variation in water stress, grid headroom and specific generation sites, and social contrasts between municipalities within a province—which only a comarcal or municipal resolution (Section 4.8) could capture. These rankings should be read as strategic, provincial-scale screening priorities, not as site-specific recommendations: the provincial scale is the finest at which all four dimensions are consistently available nationwide, and it necessarily averages over within-province variation in land, grid, water, port and industrial-cluster conditions, which must be assessed at the comarcal or municipal scale before any individual site is chosen. Above it, a subset of criteria is available only at the autonomous-community level and had to be apportioned to provinces (C5, C8, C12),

forcing provinces of the same community to share a value; the effect of this apportionment is quantified in Section 3.5. The analysis is, moreover, a static snapshot of a fast-moving project pipeline. Although the dataset is broadly of the 2023–2025 period, individual criteria carry their own vintages—for example grid capacity is a 2026 resolution and industrial CO_2 a 2022 figure—so the ranking mixes reference years, a further reason to read it as a snapshot rather than a synchronous state. Fourth, the carbon criteria (C7, C8) score the availability of CO_2 near a province but not the energy and economic cost of transporting that CO_2 from the emitting point source to the production site, which would penalize dispersed sources; incorporating CO_2-transport cost is left to future work. Fifth, the open re-implementation used for the sensitivity and robustness analyses reproduces the SOCRATES rankings closely but not exactly ($\rho = 0.91$ methanol, 0.84 ammonia, with a different ammonia leader), and its fast sensitivity heuristic agrees with the full multi-start search to a high correlation (mean Spearman $\rho \approx 0.96$, top-ten overlap 8–9/10 per weight vector) rather than identically; because the robustness conclusions are read from distributions over many weightings and the robust core is common to both implementations these differences do not affect them, but the residual gap—concentrated on the weight-dependent ammonia leader—should be kept in mind. Finally, a few criteria rest on proxy variables—most notably C15, where recorded renewables *conflict* (litigation, moratoria and press-reported opposition) is used, and the absence of recorded conflict must not be read as acceptance, since it may instead reflect fewer projects, weaker mobilization capacity or unequal access to legal remedies—whose construction could be refined; its *coding*, however, does not materially affect the ranking, which is stable across alternative definitions of the index (Section 3.5).

4.8. Future Work

The limitations map directly onto the natural lines of continuation. A first direction is to move from the provincial to the comarcal or municipal scale, where siting decisions actually materialize and where the availability of land, water and grid can be pinned down more precisely. A second is to give the model a temporal dimension, updating it as the project pipeline matures and infrastructure evolves. It would also be valuable to broaden the sensitivity analysis to the within-dimension weights and the preference thresholds, and to explore a multi-actor weighting that records the priorities of different stakeholders. A priority for follow-up is to replace the absolute count-based criteria with size-aware measures—committed electrolyzer capacity, multi-year investment, per-working-age education supply—once comparable provincial data become available, since Section 3.5 shows the ranking is sensitive to this choice. The framework is directly extensible to further derivatives, such as synthetic aviation fuels, which would complete an integral assessment of the renewable-hydrogen value chain in Spain. Finally, while the approach itself is general, its present implementation relies on SOCRATES and on EU and Spanish public databases; replicating it outside the EU would require sourcing equivalent indicators and confirming their comparability, so cross-context transfer is a matter of data compatibility rather than of the method.

5. Conclusions

The most general and robust finding of this study is that incorporating social need explicitly shifts the geography obtained under the adopted weighting for renewable hydrogen derivatives in Spain toward the south and interior—a priority geography under a distributive-justice lens, not an objectively optimal one—away from the wealthier northern poles and large urban centres that a conventional techno-economic analysis would favour. In both derivatives, provinces of high social vulnerability rise to the top when they also meet reasonable technical and economic conditions—confirming the paper's starting hypothesis

that greatest need and genuine potential often coincide. A robust core—Murcia above all, with Zaragoza, Asturias and an Andalusian arc close behind—ranks high for either methanol or ammonia across the weight space. Capturable CO_2 is the single factor that separates the two geographies: methanol gravitates to where industrial carbon and port infrastructure meet, ammonia to where renewable resource and talent concentrate.

The principal contribution is not the rankings themselves but the evaluation framework built to obtain them: a transparent, replicable approach, assembled entirely from public data, that makes the social value judgement explicit and quantified and that distinguishes robust recommendations from circumstantial ones. Its results should be read as planning guidance rather than as the designation of winners: the stable core as a weight-robust foundation for early deployment, the weight-sensitive leaders with due caution. Making social need a primary siting criterion, then, is not only feasible; it redraws the industrial map, steering the emerging hydrogen economy toward the territories that stand to gain most from it. And because nothing in the method is particular to Spain, to these two derivatives or to this weighting, the same framework can guide just-transition siting for other regions, molecules and priorities. Deciding where the green economy is built is, in the end, a social choice as much as a technical one—and it can be made in the open.

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Data Availability Statement: All criteria data derive from publicly available sources detailed in Appendix A. The assembled 50 × 19 impact matrix and an open Python implementation of the SMCE/Kemeny model (Appendix B), which regenerates every ranking and figure in this paper from public data, are openly available on Zenodo at https://doi.org/10.5281/zenodo.23412083 (DOI: 10.5281/zenodo.23412083). The repository also includes a criterion-level data dictionary documenting, for each criterion, the indicator and source, the normalization and coding rules (including for the C15 conflict index), the provincial-allocation formulas for community-level variables, and the exact computational settings.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Criteria Data and Sources

This appendix documents the provenance of every criterion and reproduces the full 50 × 19 impact matrix on which all rankings are computed. Table A1 gives, for each criterion, the exact indicator and units, the optimization direction and the source with its vintage.

Tables A4 and A5 list the criterion values for the 50 provinces; the same data are released in machine-readable form as `impact_matrix.csv` (Appendix B).

Table A1. Criteria, indicators and data sources. Dir.: optimization direction (MAX/MIN). Scenario "M" marks criteria used only in the methanol scenario (C7–C8); all others apply to both.

Code	Criterion	Indicator (Units)	Dir.	Source (Vintage)
C1	Solar resource	Annual mean GHI ($kWh/m^2/yr$)	MAX	PVGIS 5.3/SARAH3, JRC (2005–2023)
C2	Wind resource	Mean wind speed at 100 m, maximum-resource site (m/s)	MAX	Global Wind Atlas 3.3; ERA5 via Open-Meteo (2005–2023)
C3	Water availability	Water Exploitation Index WEI+ by hydrographic basin	MIN	MITERD, 3rd-cycle river-basin plans (RD 35/2023)
C4	Land free of Natura 2000	% territory outside Natura 2000 protected areas (SAC + SPA)	MAX	MITERD, Nature Data Bank (Dec 2024)
C5	Grid access capacity	Available demand connection capacity (MW)	MAX	Red Eléctrica de España, GRT resolution (2026); CCAA level
C6	Port access	Road distance to nearest bulk-liquids/chemicals port (km)	MIN	Puertos del Estado
C7	Capturable industrial CO_2	Industrial CO_2 (kt/yr)	MAX	EEA Industrial Reporting DB v13/PRTR (2022); M
C8	Capturable biogenic CO_2	Biogenic CO_2 from biomethane upgrading	MAX	Sedigas (2023); M
C9	Industrial weight	Industrial GVA as % of provincial GVA	MAX	INE, Regional Accounts, file 76926 (2023)
C10	Renewable H_2 projects	No. of projects at TRL ≥ 7	MAX	IIT-ICAI H_2 Observatory (2025); AeH2 (2024); IDAE PERTE ERHA
C11	Industrial H_2 investment	Gross FDI in H_2-chain CNAE sectors (M EUR)	MAX	DataInvex, Sec. of State for Trade (2023)
C12	Social vulnerability	Adjusted AROPE rate (%)	MAX	INE ECV (2025); EAPN-ES; INE Income Atlas (2023)
C13	Unemployment rate	Annual mean unemployment (%)	MAX	INE, Labour Force Survey (2024)
C14	Depopulation index	% municipalities <12.5 inh/km^2 and 2011–2024 change	MAX	MITERD (sparsely populated zones); INE Padrón (2011, 2024)
C15	Renewables conflict	Composite conflict index (litigation, moratoria, opposition)	MIN	CENDOJ/vLex (2022–2024); specialized press
C16	Population 25–44	% of provincial population	MAX	INE, Padrón (2024)
C17	Active STEM graduates	% active population with a STEM degree	MAX	INE Census (2023); Ministry of Universities (2022–23)
C18	Industrial VET supply	No. of centres in four industrial VET families	MAX	TODOFP, Ministry of Education (2022–23)
C19	Engineering degrees	No. of active engineering Bachelor programmes	MAX	RUCT, Ministry of Science (2024)

1. Data processing.

A few criteria required harmonization. Grid access capacity (C5) and capturable biogenic CO_2 (C8) are published at the level of the autonomous community and were apportioned to provinces, so provinces of the same community share their value; the AROPE rate (C12) was likewise adjusted from regional to provincial level, using each province's relative position in the INE Income Atlas as the disaggregation key, so that provinces of the

same community are differentiated by their relative income rather than sharing a single regional value. The renewables-conflict index (C15) rests on proxy variables, combining active administrative litigation, the presence of a regional moratorium or tax, and organized local opposition. Finally, the two carbon criteria (C7–C8) enter only the methanol scenario; note that, under Delegated Regulation (EU) 2023/1185, CO_2 from fossil-fuel electricity generation is eligible only until the end of 2035 and CO_2 from fossil-fuel combustion in industry until the end of 2040, after which (from 2041) only biogenic CO_2 meeting the sustainability criteria, atmospheric (direct-air-captured), geological, and recycled-carbon/renewable-fuel-combustion CO_2 remain admissible (see Section 4.2).

2. Data dictionary and processing rules.

The Kemeny aggregation is ordinal per criterion: each criterion enters only through its optimization direction (Table A1) and the resulting provincial order, so no cardinal normalization (min–max or z-score) is applied. Table A2 lists the criteria that require coding or spatial-allocation rules beyond this; the others are used as published. The Kemeny median is solved by multi-start local search (eight starts—a net-flow order, a Borda order and six seeded random permutations—refined by best-insertion moves), and the global weight-sensitivity sweep draws $M = 1500$ Monte-Carlo weight vectors per scenario under a per-dimension cap of 0.5. A complete, machine-readable version of this dictionary is released with the repository (Appendix B). The component-level definition of C15—the litigation and organized-opposition counts, the binary moratorium/tax flag, their 3/10/2 weighting, the 2022–2024 window, the zero value assigned to provinces with no recorded events, and the per-component sources—is summarized in Table A3 and documented in full in the released data dictionary (`DATA_DICTIONARY.md`), so the index can be reconstructed independently.

Table A2. Data dictionary: criteria requiring coding or spatial-allocation rules beyond the ordinal direction of Table A1. All other criteria are used as published.

Criterion	Coding/Spatial-Allocation Rule
C5 Grid access capacity	Published at the autonomous-community level and apportioned to provinces (provinces of the same community share the value).
C7 Capturable industrial CO_2	Registered industrial point-source emissions used as an availability proxy; the recoverable fraction depends on capture configuration and flue-gas concentration, which are not modelled.
C8 Capturable biogenic CO_2	Biogenic CO_2 from biomethane upgrading (Sedigas) under a uniform (~90%) capture rate that cancels under the ordinal aggregation; apportioned from community to provinces.
C12 Social vulnerability (AROPE)	Regional AROPE (INE ECV) disaggregated to provinces using each province's relative income in the INE Income Atlas as the key.
C14 Depopulation index	Composite of the share of municipalities below 12.5 inhab/km^2 and the 2011–2024 population change.
C15 Renewables conflict	Ordinal composite (direction MIN), 3 × litigation + 10 × moratorium/tax (1/0) + 2 × organized opposition, over 2022–2024; provinces with no recorded events take the minimum.

Table A3. Component-level coding of the renewables-conflict index C15 (direction MIN). The composite is 3 × litigation + 10 × moratorium/tax + 2 × opposition, measured over 2022–2024; provinces with no recorded events in any component take the value 0. Full per-province source assignments are in the released data dictionary (`DATA_DICTIONARY.md`).

Component	Scale	Coding Rule	Weight
Administrative litigation	integer count ≥ 0	number of administrative-court appeals (TSJ/TS and regional high courts) against renewable-energy projects filed in the province in 2022–2024	3
Regional moratorium/tax	binary $\{0, 1\}$	1 if a regional moratorium on new renewable permits or a specific regional tax on renewables was in force in 2022–2024, else 0	10
Organized local opposition	integer count ≥ 0	number of distinct organized local opposition platforms or campaigns active in the province in 2022–2024	2

Table A4. Impact matrix, criteria C1–C10 (units and directions in Table A1).

Province	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Álava	1298	13.8	0.09	78.8	1663	60	2310	115	31.2	1
Albacete	1825	11.4	0.52	76.9	2707	170	290	310	20.1	1
Alicante	1786	11.4	0.52	62.2	3330	15	3120	170	12.1	2
Almería	1884	12.0	0.61	70.2	13,100	10	5430	150	6.07	7
Asturias	1298	13.8	0.06	73.0	1248	30	18,420	130	21.6	8
Ávila	1686	11.4	0.18	73.8	15,256	280	110	520	10.9	1
Badajoz	1824	8.64	0.44	69.7	6231	190	3820	400	13.8	14
Baleares	1763	10.7	0.55	75.1	784	10	440	75	5.54	1
Barcelona	1662	11.2	0.21	69.3	201	10	4720	350	18.6	5
Burgos	1580	13.8	0.18	73.8	15,256	115	2080	760	29.9	3
Cáceres	1811	10.6	0.31	69.7	6231	230	250	260	25.8	6
Cádiz	1903	13.3	0.61	70.2	13,100	30	4980	160	14.1	7
Cantabria	1233	14.6	0.09	72.5	1106	10	640	125	21.7	1
Castellón	1768	13.7	0.52	62.2	3330	10	8940	140	26.8	3
Ciudad Real	1839	8.12	0.44	76.9	2707	280	190	360	21.8	5
Córdoba	1879	7.73	0.48	70.2	13,100	145	1540	420	13.9	5
Cuenca	1748	9.60	0.52	76.9	2707	150	220	270	22.9	0
Gerona	1567	15.8	0.21	69.3	201	105	690	135	17.0	1
Granada	1869	12.5	0.61	70.2	13,100	70	1210	290	9.36	3
Guadalajara	1751	10.6	0.31	76.9	2707	210	1080	240	30.9	0
Guipúzcoa	1267	12.5	0.09	78.8	1663	80	2540	110	26.4	2
Huelva	1917	8.11	0.48	70.2	13,100	10	11,200	200	22.5	12
Huesca	1743	16.6	0.21	71.5	0	250	1820	430	21.3	4
Jaén	1868	10.3	0.48	70.2	13,100	140	870	210	14.3	2
La Coruña	1388	13.3	0.05	88.0	13,580	10	2980	230	19.3	5
La Rioja	1467	11.9	0.21	64.3	327	150	580	120	26.4	1
Las Palmas	1884	16.9	0.75	52.8	829	10	1240	60	6.49	2
León	1678	13.2	0.18	73.8	15,256	135	6100	810	16.4	3
Lérida	1729	15.6	0.21	69.3	201	100	760	340	17.5	1
Lugo	1436	12.3	0.07	88.0	13,580	95	310	220	15.7	1
Madrid	1780	11.3	0.31	60.2	0	350	180	100	8.57	5
Málaga	1897	13.3	0.61	70.2	13,100	10	480	145	6.08	3
Murcia	1817	10.4	0.89	76.4	5985	50	6820	320	20.7	8
Navarra	1574	14.7	0.21	73.0	0	155	1680	280	29.9	5
Ourense	1503	11.5	0.07	88.0	13,580	100	270	180	20.1	1
Palencia	1690	14.6	0.18	73.8	15,256	190	1950	490	31.7	2
Pontevedra	1479	10.5	0.05	88.0	13,580	25	350	190	20.9	3
Salamanca	1739	10.5	0.18	73.8	15,256	270	520	980	11.7	1
Santa Cruz de Tenerife	2080	15.8	0.75	52.8	829	10	890	50	6.56	2
Segovia	1634	11.2	0.18	73.8	15,256	260	150	580	17.4	0
Sevilla	1904	10.3	0.48	70.2	13,100	10	4350	450	14.8	6
Soria	1648	11.7	0.18	73.8	15,256	200	90	560	27.2	1
Tarragona	1698	15.6	0.21	69.3	201	10	16,850	300	24.0	5
Teruel	1724	11.6	0.21	71.5	0	145	130	390	17.7	3
Toledo	1787	8.71	0.31	76.9	2707	280	980	380	23.8	1
Valencia	1771	9.61	0.52	62.2	3330	10	3540	250	19.7	5
Valladolid	1709	6.92	0.18	73.8	15,256	210	1390	690	26.4	3
Vizcaya	1279	12.6	0.09	78.8	1663	10	9870	105	20.1	4
Zamora	1733	10.6	0.18	73.8	15,256	220	390	870	18.2	1
Zaragoza	1736	13.3	0.21	71.5	0	160	7650	470	25.3	8

Table A5. Impact matrix, criteria C11–C19 (units and directions in Table A1).

Province	C11	C12	C13	C14	C15	C16	C17	C18	C19
Álava	233	14.7	7.17	29.2	5	24	9.41	54	0
Albacete	22.4	34	14.3	25.9	10	22.7	4.32	40	3
Alicante	58.1	30.7	15.0	9.18	10	25.4	6.32	98	16
Almería	8.74	34.7	14.3	13.5	5	25.8	4.45	52	8
Asturias	468	22.4	9.88	28.4	8	23.3	7.74	82	18
Ávila	1.19	24.1	8.64	55.4	5	21.8	4.48	22	8
Badajoz	30.2	30.4	17.1	43.4	23	22.8	4.95	50	23
Baleares	0.01	15.2	9.38	7.44	0	26.4	5.75	58	4
Barcelona	524	21.3	8.92	7.08	10	27.1	8.16	224	100
Burgos	3.80	24.1	9.16	51.7	13	23.5	6.89	56	11
Cáceres	20.7	30.4	18.3	47.0	18	22.5	4.54	36	0
Cádiz	11.2	34.7	23.3	12.1	13	24.5	5.51	64	11
Cantabria	0	19.2	7.84	23.1	5	23.9	8.23	58	17
Castellón	22	30.7	14.1	15.6	15	25.2	7.34	68	7
Ciudad Real	27.1	34	18.7	45.0	18	22.9	4.67	48	14
Córdoba	8.19	34.7	22.1	31.4	8	24.4	5.45	66	8
Cuenca	12.7	34	14.1	62.1	10	22	3.96	28	1
Gerona	72.3	21.3	8.46	16.4	5	26.8	7.73	74	8
Granada	8.46	34.7	21.1	19.0	8	23.6	5.56	62	8
Guadalajara	16.3	34	13.4	44.5	5	26.5	5.13	32	0
Guipúzcoa	467	14.7	7.64	15.7	5	24.1	11.4	84	11
Huelva	6.83	34.7	13.7	17.3	13	25.1	6.08	50	9
Huesca	25.9	19.1	8.49	37.1	23	23.8	6.26	46	0
Jaén	5.46	34.7	20.7	40.7	5	22.3	4.37	38	15
La Coruña	146	22.1	7.85	33.4	70	24.3	6.14	88	21
La Rioja	0	22.8	9.27	23.2	28	23	7.54	40	9
Las Palmas	0.02	31.2	16.3	8.88	0	24.8	5.69	56	18
León	2.95	24.1	11.3	60.5	10	22.6	5.02	46	15
Lérida	39.0	21.3	6.64	26.9	10	24.7	7.66	54	8
Lugo	45.2	22.1	5.50	51.2	32	22.2	5.06	38	0
Madrid	2077	19.4	8.13	5.58	5	27.8	9.20	198	190
Málaga	15.6	34.7	15.8	6.30	5	25.9	5.62	90	14
Murcia	370	32.5	13.6	12.8	5	25.7	6.45	92	28
Navarra	3.30	16.5	9.12	24.2	37	24.6	9.55	72	21
Ourense	38.2	22.1	9.72	56.7	24	21.6	4.81	36	0
Palencia	1.91	24.1	7.67	54.2	10	21.9	5.68	30	0
Pontevedra	118	22.1	10.4	27.3	48	23.7	6.20	74	15
Salamanca	2.48	24.1	9.05	49.2	5	22.1	6.62	42	21
Santa Cruz de Tenerife	0.02	31.2	13.8	8.16	0	23.1	5.36	52	7
Segovia	1.41	24.1	8.46	52.7	5	21.7	4.96	26	1
Sevilla	17.2	34.7	16.7	11.2	10	25	6.42	110	30
Soria	0.99	24.1	7.87	56.5	18	21.4	4.59	18	0
Tarragona	73.7	21.3	13.0	14.8	10	25.3	8.21	86	11
Teruel	19.2	19.1	8.63	56.1	20	22.4	5.17	30	0
Toledo	31.3	34	18.6	27.4	15	23.4	4.32	48	0
Valencia	94.5	30.7	12.7	10.4	28	25.6	7.37	142	39
Valladolid	4.52	24.1	10.9	14.2	5	23.2	6.80	64	27
Vizcaya	728	14.7	7.48	18.1	5	24.2	10.7	98	30
Zamora	1.34	24.1	10.7	64.5	13	21.5	4.39	28	0
Zaragoza	119	19.1	10.5	30.2	33	24.9	8.19	96	18

Appendix B. Open Reproduction of the SMCE Model

To make the analysis independent of proprietary software and fully reproducible, we re-implemented the Social Multi-Criteria Evaluation procedure as a compact, open Python routine. It reads the public 50 × 19 impact matrix and the per-criterion optimization directions; for a given weighting it builds the weighted, non-compensatory pairwise outranking matrix $E_{ab} = \sum_k w_k P_k(a, b)$, where $P_k(a, b) = 1$ if province a is preferred to b on criterion k, 0.5 under indifference and 0 otherwise; and it returns the Kemeny median order, i.e., the ranking maximizing $\sum_{a \text{ before } b} E_{ab}$, obtained by multi-start local search: eight starting orders—a net-flow (Copeland-like) order, a Borda (row-sum) order and six seeded random permutations—are each improved to a local optimum by best-insertion moves, and the highest-scoring order is retained. The global weight-sensitivity sweep, which recomputes the ranking for many weightings, uses a faster net-flow-plus-adjacent-swap heuristic; it agrees with the full multi-start search to a high correlation (mean Spearman $\rho \approx 0.96$) rather than exactly, which does not affect the distribution-based robustness conclusions. Dimension weights are split evenly among the active criteria of each dimension, and the two scenarios differ only in the presence of criteria C7–C8.

Validated against the published SOCRATES rankings, the open implementation attains a Spearman rank correlation of $\rho = 0.91$ (methanol) and $\rho = 0.84$ (ammonia), an identical methanol leader (Huelva) and the same robust core (Murcia, Zaragoza, Asturias, the Andalusian arc); the residual differences are consistent with SOCRATES's internal preference/indifference thresholds, which the open version does not attempt to replicate, and—for ammonia—concentrate on the scenario leader that the sensitivity analysis itself shows to be weight-dependent (Table A6). The dimension sub-rankings (Figure 2) and the weight-sensitivity analysis (Figure 6) are produced with this routine. The impact matrix and the code are released so that every ranking in the paper can be regenerated from public data with a single command.

Table A6. Agreement between the published SOCRATES rankings and the open Python re-implementation, over the 50 provinces.

Scenario	Spearman ρ	Same Leader	Top-5 Overlap	Median Rank Shift
Green methanol	0.91	Yes (Huelva)	4/5	3
Green ammonia	0.84	No	3/5	3

Top-5 overlap counts provinces common to both top-five sets. Median rank shift is the median absolute difference in provincial rank between the two implementations. In the ammonia scenario the published leader (Sevilla) and the re-implementation's leader (Huelva) differ; as the sensitivity analysis shows, this top position is weight-dependent. Residual differences trace to SOCRATES's internal preference/indifference thresholds, which the open routine does not replicate.

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